Humanity and Space:
The Future of Space Exploration

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1 Abstract

Our goal is to create a plan for a permanent human presence on the Moon and by extension create a steppingstone for humanity to reach further into space. We will analyze existing data and suggest new solutions for different propulsion methods, base locations and materials, protection methods, and ways of constructing and utilizing robots to find the best for each scenario. Finally, we will recommend what we believe is best for each category and how we believe humanity should proceed.

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2 Introduction

Our IQP seeks to create a plan for humanity to advance further into space. We believe this expansion of our species is not only necessary but inevitable to both better understand the universe we live in and protect ourselves from ever looming threats from outer space such as asteroids or solar flares. In this IQP we combine both current research and our own novel ideas into a plan to guide humanity in our first steps into this future.

In the future, Humanity will need a sustained presence in space to be able to conduct larger-scale operations both at and around the bases as well as further into space, for which missions the bases will serve as starting points. The two most likely and best starting points for this are the Moon, followed by Mars. We believe the optimal base design for the future will include a primary base orbiting the Moon, with a small outpost from which to conduct research and exploration, and ultimately a fully sustained, large-scale base on the surface of the Moon to work in tandem with the orbiting base. While this self-sufficient surface base is conceptualized and designed it will be supplied and supported by the orbiting base. A similar process will happen on Mars, though likely not as much work will be done on that until the Moon base is complete. The orbiting bases will grow food and recycle needed materials, and this will aid the work of the humans and robots on the surface. This will be especially important in the construction phase of the surface base.

With a human presence completely secure, new propulsion methods will be used to aid in further explorations into space, as well as for use in transportation between established bases. Primarily, the propulsion methods will need to be updated. Along with new propulsion methods, new methods of fuel synthesis will be used. Solar sails will be used extensively, possibly even able to harness microwave background radiation. Also, fuel will be synthesized from asteroids, which will allow humans and robots in space to use the environment to their advantage. These methods of propulsion and fuel synthesis will both allow for faster and more efficient transport between active bases as well as transport to and from Earth for the bases in orbit and on the surface of the Moon and Mars.

As the human presence in space grows, there will be two more large developments that are currently only in the earliest stages to aid in both prolonged presence and further space exploration. The first will be human engineering. This will be controversial and expensive, but Humans will be engineered to better withstand radiation and to be better suited to a lower gravity environment. While artificial gravity systems and high-quality spacesuits will be created, improved upon, and used widely, it will ultimately be more cost effective to make humans better suited to the environment as opposed to altering the environment to suit humans.

One of the most important aspects of the future for Humanity in general along with space exploration will be artificial intelligence. AI will become a peer to humans, and most of the work will be taken on by AI initially. Over time, different jobs will emerge that can be filled by humans, but the use of technology will be changed forever. The robots operating on the surfaces with human bases will be equipped with not only AI, but also the latest mechanical and electrical innovations. This will allow robots to not only work better on human controlled bases, but also act autonomously on robot-only bases and on robot-only missions deeper into space than it is plausible or worthwhile to send humans. Eventually, Robotic systems will replace human astronauts, and the human role will shift to exclusively controlling missions, where they will also be assisted by AI.

3 Executive Summary

Our IQP seeks to create a plan for humanity to advance further into space. The first steps of this include building a permanent base on or around the Moon to act as both a center for research, a protection measure for earth against any threat from space such as a large meteor, and to launch missions to distant planets. In this IQP we combine both current research and our own novel ideas into a plan to guide humanity in our first steps into this future.

A permanent human settlement on or around the Moon will be beneficial for several reasons. Humans will be able to research the effects of prolonged space and radiation exposure, the viability of growing different plants and food sources more easily in space, and practice techniques for setting up bases on distant planets which will all aid in future missions to further celestial bodies. To do this we need an economical and effective mode of propulsion as well as a plan to create and maintain the lunar base.

In creating a lunar base, the safety and health of the personnel is extremely important. Cosmic radiation is one of the most prevalent health risks to astronauts spending extended periods in outer space. It has been shown that excessive exposure to sources of radiation can shorten the telomeres which protect the ends of our chromosomes and the integrity of our DNA. Shortened telomeres, associated with many of the effects of aging, result in an increased risk of cardiovascular disease, cancer, and several other immunocompromising diseases [28].

Since radiation is such a concern for the health of humans, it must be carefully considered when building the base. The optimal area for construction of a surface outpost that is to be used for prolonged activity will be in an area that is protected to the maximum possible extent from radiation. According to this theory we believe the optimal location for building a human-operated outpost will be surrounding the ridges of The Shackleton Crater, at 89.54 degrees south, 0 degrees east [11]. While building a base in one of the Moon's old lava tubes offers full protection from radiation and has been considered before, it will come with other challenges such as higher difficulty construction and its relative inaccessibility to the surface. Instead, this alternative method will use the natural advantages of the surface of the Moon as a radiation shield.

Temperature is also a major concern. To make the outpost safe while using as little energy as possible, heat retention needs to be maximized. Along with its ability to protect against radiation, lunar regolith is also very effective at retaining heat, meaning far less power is needed to heat the outpost that is coated with a regolith compound material than it is to heat an outpost without a layer of regolith protecting it [14].

Since the topography of the Moon cannot be used to shield an orbiting base, another method must be used. Given the promising results of the use of regolith-based materials to protect the grounded outpost from radiation and maintain safe internal temperatures efficiently, the proposed orbital outpost will be constructed with a protective layer of regolith-polyethylene-aluminum compound material. The regolith should be compressed to $4.0\frac{g}{cm^3}$, with areal density of at least $250\frac{g}{cm^2}$, along with a 5 cm to 10 cm layer of polyethene, and 3 mm of aluminum for structural integrity. While this will be difficult to initially make enough of to cover the entire orbital component of the base, this material should be used on large parts of it, and, ideally, eventually on the entire orbital component.

Radiation protection is also important for robots. There are two primary effects that radiation has on robots. First, there are single-event effects, where electric particles cause bit flips in digital circuits and voltage spikes in analog circuits, which can affect the data. While this is not a long-term effect, it can lead to computer errors, which is not desirable for robots collecting valuable data. The second effect of radiation on electronics is called a total ionizing dose effect. This effect is long term and creates electron-pair holes in the robot’s electronics. These can affect and destroy transistor parameters, as well as causing circuit leakage [16]. To combat this problem robots must be built with radiation-hardened electronics [16]. There are multiple ways to achieve radiation hardening. The first method is to either create the device out of or protect parts of the device with a radiation absorbing material, such as lead or tungsten. Another method is to create components that are naturally less susceptible to radiation. One way of doing this is to embed the electronics in materials that can deter the effects of radiation [16].

These robots will be used for exploration of the Moon and later other celestial bodies. The goal is to eventually have robots be more effective than humans at exploration, allowing humans to be able to control missions from relative safety while the robots undertake dangerous missions. For broad-scale lunar exploration on the surface, robots able to hover above the ground to avoid gathering electronic destroying lunar dust robots is promising. However, for exploration of lunar caves, which are currently sought-after places to map and explore, a different system will need to be used. Robots are not able to use solar panels in the tubes, so a different method of supplying power will need to be used. A research team at The University of Oviedo developed a proposed method of lava tube exploration for the European Space Agency. This proposed method has a large robot stationed outside the entrance to the lava tube, from which is lowered down a “Charging head” [23], which supplies power to the robots that are exploring inside the cave through wireless power. Some of the robots in the cave would be able to act as intermediaries, transmitting power from the wireless charging station lowered down the tube to the robots that are further along in the tube [23].

While radiation is a major concern, it is not the only one. Food, water, supplies, and the rotation of personnel also needs to be considered. In the early stages of the lunar outpost and orbital station, food and water will need to be brought from Earth. Shipping costs to space are incredibly high [14], and logistically this is not ideal. However, there are two things that will be utilized to make human existence possible without constant shipments of food and water from Earth. First, hydroponics will be used to grow food. This should be done on the orbital component of the base wherever possible to keep the surface base as small as possible, and because many of the humans will always be on the orbital component of the base. Water can be gathered by robots from the ice inside Shackelton Crater. Robots that would harvest the ice in the crater needing less radiation protection to begin with (less exposure to SPE’s and GCR’s), making it a cost-effective mission, and it will not be a long journey from the ice location to the base location where it can be launched to the orbital component.

Another important aspect of a robotic presence on the Moon is outpost maintenance. To keep the outpost properly maintained, especially as it grows larger and more complex in its later stages of development, robots will need to do work on and around the outpost as well. There are two main sections of the base that will need frequent maintenance. First, and most importantly, the base will have solar panels set up in the section of Shackelton Crater that is in perpetual light. These solar panels will be protected from radiation, but they will still be damaged so repairs will need to be made due to the extreme nature of lunar radiation, as well as the naturally harsh environment on the Moon. Robots will need to travel to these solar panels to replace and repair them. The second area where robots will be needed it in maintenance of the other robots. Robots will wear down over time due to radiation and the Moon’s hostile environment. In the earliest stages of the outpost, there will not be enough humans on the base to maintain all the robots necessary. Instead, there will be one technician who will serve as a manager for a team of robots that specialize in maintaining the exploration fleet.

Even with the base planned out, there is still the problem of propellants. For the journey into Earth's orbit a chemical fuel will likely be necessary. While it has a low specific impulse, it is a high-thrust fuel compared to other electric propulsion methods and so is superior in this application. Once Earth's orbit is escaped and the high-thrust is not necessary anymore, we recommend an electric propulsion method like Hall-Effect. Electric propulsion typically offers significantly higher specific impulse compared to chemical propulsion. A high specific impulse of the fuel means less of it in terms of weight is needed for the same impulse. This comes at the expense of lower thrust-to-power levels, however, meaning electric propulsion cannot output thrust quickly and needs to operate for far longer to produce the same amount of total impulse. Electric propulsions high impulse also makes it ideal for situations such as maintaining orbit for our proposed lunar orbital base or for long term missions to places like Mars where its lack of thrust is not a significant issue or can be compensated for in other ways.

There are even some novel nuclear propellants to consider. Magnetic Fusion Plasma Engines (MFPE) combine elements of fusion propulsion, ionic propulsion, and other concepts. The advantage of the method is the fact it can provide thrust and power for the ship from a single energy source which could lessen, or eliminate, the need for solar panels on board thereby reducing the weight and fuel needed. MFPEs also produce a high specific impulse, use extremely energy dense fuels, have the possibility of using magnetic and physical structures of the propulsion system to shield from radiation, doesn't depend on being close to a star, and minimizes the risk of radioactive contamination compared to nuclear-thermal or fission-electric concepts since it requires less radioactive material and may allow for a safer reactor shutdown.

For long term missions and keeping stations and satellites in orbit, we believe electric propulsion is the best option. It produces a high specific impulse compared to the other options and the low thrust is less impactful as there is little need for quick changes in direction. The highest specific impulse is produced by Hall-Effect Electric Propulsion, which is consistently at or around 1000 - 1400 sec and Electrospray Electric Propulsion which reaches up to 3500 sec with Indium (FEEP) propellant.

4 Author's Notes

4.1 Benjamin Guilbault

What motivates me most about this project is the possibility of improving our current technology or creating new technology that would allow us to make safer and quicker flights farther away from Earth than we can now with a reasonable amount of money. These advancements could contribute massively to creating a possible outpost on planets like Mars and to gather resources that are unavailable or in short supply on Earth which could lead to many things such as better and cleaner power generation as discussed in a different topic of this IQP.

This project relies on an understanding of physics, thermodynamics, material properties, and electricity and magnetism, as well as other fundamentals taught in the classes I have taken for my major at WPI. This project also contributes to my career goals as I am currently interested in space, specifically in planetary outposts. This project will help me learn more about these topics which will allow me to research even further once the project is complete and boost my job prospects in the future.

I believe this project qualifies as an IQP because of its broad scope which allows students to pick a topic interesting to them and dive deeper into it, finding problems to solve, and advancing our understanding and future options instead of rewording findings already made by others. The topics this project covers are also extremely important in humanity's future as we move both away from fossil fuels and deeper into space, we will very likely have to solve the problems posed in this IQP.

My goal in this project is to come up with and test the validity of different ways to propel humans and supplies through space and deliver them to distant bodies. I will test different starting points (Earth / Moon outposts), methods of propulsion, sizes of cargo, and techniques to alter the flight path once launched. This will hopefully weed out any currently unfeasible methods or techniques and highlight promising ones for scientists and engineers to further test and utilize. To disseminate this project, I believe a published paper is the most realistic option.

4.2 Camille Williams

From reading about exciting developments of the Hubble telescope in elementary school, to my first time seeing the Milky Way, I have been fascinated by outer space for as long as I have been in school. My interest in astrophysics has driven my application of physics and mathematics in my program at Worcester Polytechnic Institute (WPI) and it is a primary motivator for my choice of topic for my Interactive Qualifying Project (IQP), Humanity & Space-- In-Space Propulsion.

I started at WPI in aerospace engineering and not Math or Physics. While I still find applications in aerospace particularly engaging, I did not find what I was seeking in a degree program. I wanted a bachelor's degree which would equip me to fundamentally understand problems and approach them creatively. I felt this was not afforded to me as much in application-based understanding. Yet, the loss of specificity in this change has also come at the cost of complications breaking into astrophysics industry/research at a bachelor's degree level. While I do hope to continue into a PhD program in either astrophysics or electrical engineering, this is a longer-term pursuit. In choosing the Humanity and Space IQP, I realized an early opportunity to contribute to this area of my deeper interest.

An additional motivating factor in choosing my IQP has been my active research with Professor Vadim Yakovlev in the Mathematics department at WPI. I have worked with Professor Yakovlev for the past two years on a characterization approach for microwave plasma in Finite Difference Time-Domain electromagnetic simulation. I was initially concerned that this work did not directly relate to my long-term goals, but in reading about plasma propulsion and other creative applications of microwaves/RF in astrophysical research I soon realized otherwise. Ultimately, these connections inspired my choice to focus on in-space propulsion.

My end-goal with this IQP is to propose an energy-efficient, sustainable propulsion plan for the continuous orbit of a shuttle about the Moon and the Earth. Sufficient information for this proposal requires an understanding of heritage propulsion methods, novel propulsion methods, and the limitations of each considered.

4.3 Will Perri

My motivation for taking the Humanity and Space IQP is to study and discover new possibilities in space exploration to benefit humanity. My choice to investigate the use of robotics for space exploration is motivated by two factors. First among these are safety concerns, as sending robots to locations before humans will ensure that the best possible decisions are made regarding the safety of humans that will be sent afterwards. Second, but still related to safety, are the abilities of robotic systems to be sent further and to operate in harsher conditions than humans can. Ideally, in the future humans and robots will be able to work together in space exploration to maximize the potential findings of missions, and to collect better data that either humans or robots would be able to do apart. I am a Mathematical Sciences major, minoring in Computer Science, with my mathematical program specifically focused on software applications and optimization. This project relates to my program of study by investigating both the mathematics of space exploration, and the applications to robotic systems in space. This project is related to my career goals, as my goal is to work in software on robotic systems, and my goal for this project is to both deepen my own understanding of these systems and how they operate in difficult environments, as well as to discover new ideas and disseminate the results.

This project qualifies as an Interactive Qualifying Project because the topic of space is paramount in both science and society. In terms of science, space has become something that is explored constantly, and recently many more efforts have been made to both further space exploration and to investigate the possibility of long-term human presence in space. The problems that must be addressed are scientific in nature, as they require rigorous hypothesizing and multiple stages of testing. Many of the efforts that have been researched to aid in the writing of this Interactive Qualifying Project are in the earliest stages of development, even if the scientific principles underlying them are unquestionably sound. In terms of society, space is arguably the most important current issue. As climate change worsens, the possibility of energy creation in space (heavily reliant on robotics) and a sustained human presence off Earth become more necessary to explore. Similarly, nations developing conflicting interests in space exploration make this issue even more society centered. Due to the ramifications in science and society, this topic qualifies as an Interactive Qualifying Project. In this project, beyond discovering broad ideas for the future of space exploration, I wish to more deeply investigate specific issues regarding robotic space exploration. Some of the issues I wish to address include the problem of lunar regolith and its effect on electronic systems, the possibility of a robotic presence in lunar lava tubes, and the benefits and drawbacks of specific robotic devices and communication methods while in space. I then wish to identify at least one relatively new idea that has potential benefits for space exploration.

This project will benefit me by allowing me to understand more deeply the challenges and benefits of the use of robotic systems to explore space, as well as allowing me to apply and understand new mathematical models and methods in the field of robotics as it relates to space exploration. This project will benefit society by discovering new methods of space exploration, as well as identifying potential problems with certain ideas, allowing an understanding of what is most likely to work best in discovering a way to explore space that will benefit society. The final suggestions reached in this project will detail the best ways for humanity to continue to explore space, bringing with it the societal benefits of combating climate change, as well as simply allowing for a deeper understanding of space.

5 Motivations for a Lunar Outpost

Throughout the duration of the Apollo project, 24 American astronauts visited the Moon. Since then, much of the modern-day focus has turned towards the occupation of Mars. The past five decades have not seen any humans return to the Moon, but it is far from obsolete in our exploration of the universe. The National Aeronautics and Space Administration (NASA) announced the Artemis space program in 2017 [29]. This program aims to set up a sustainable presence on the Moon (and other planets to come) as well as land the first woman and person of color on the Moon. It is evident that the Moon will serve as a steppingstone to Mars, but it has several independent points of scientific value for humanity.

By establishing an extended human presence on the Moon, we will have greater capability to study prolonged radiation exposure. The harsh environment of space often exacerbates existing medical challenges from Earth. As a result, the medical necessities of extended space travel frequently coincide with medical advancements for the most pressing health complications on Earth. Long-term occupation will allow us to assess the viability of growing different plants and food sources in space. If we consider the sociological mirror to this on Earth, easily grown and preserved food could help mitigate hunger in places on Earth more susceptible to drought or natural disaster from global warming. If Earth were to ever become inhabitable, the Moon allows us the most accessible view with its thinner atmosphere to study distant stars and other habitable worlds [30]. Similarly, astronomical studies from a lunar outpost would give us the clearest view of incoming cosmic dangers (asteroids, solar flares, etc.) to life on Earth. In case of catastrophe, a lunar outpost might be used to preserve the human species in the form of frozen embryos. Finally, The Moon also contains large amounts of Helium-3. It has been proposed that if mined and used in fusion reactors it would produce energy “enough to power human energy needs for up to 10,000 years” [31].

In the following section, we expressly focus on medical advancements and potentials of Helium-3, but much more can be found on a wide variety of research topics using NASAs expansive technical reports database and ISS experimental records [32] [33].

5.1 Medical Advancement

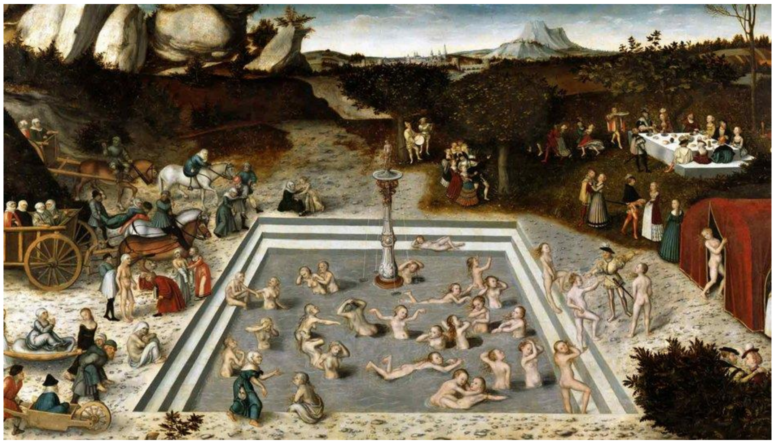
Habitable zones refer to areas surrounding a star which are hospitable to life. They must be far enough from the sun that water can exist in liquid form, but not so far that they are frozen over [34]. In the Milky Way, a habitable zone must be close enough to the galactic center to have the necessary heavy metals to form planets, but not so close that it is at high risk of an extinction event from the explosion of supernova [35]. Life is fragile and human life requires significant environmental assistance to survive, travel, and study outer space. Naturally, cutting edge technology designed to sustain human life in some of the harshest possible conditions translates indisputably to medical advancements in a terrestrial setting. In this section, we describe existing notable contributions of space science to the medical field and optimistically project its potential for extensive future years.

One of the most consistent and universal threats to human health is aging. The search for “eternal youth” is a cross-cultural phenomenon that transcends time. China’s first emperor Qin Shi Huang spent his wealth and dedicated his life to the search for immortality. He was even believed to have drunk a toxic mercury sulfide solution hoping to prolong his life [36]. Herodotus, Greek historian, and Father of History, first spoke of an age-defying cure in the 5th century,

> *Whereupon he led them, it is said, to a spring, by washing in which they grew sleeker, as though it were of oil; and it smelled of violets. So light, the spies said, was this water, that nothing would float on it, neither wood nor anything lighter than wood, but all sank to the bottom. If this water is truly such as they say, it is likely that their constant use of it makes the people long-lived [37].*

Later coined as the “Fountain of Youth”, this passage inspired countless later writings and art including German painter Lucas Cranach the Elder’s lifetime masterpiece *Der Jungbrunnen (Fountain of Youth)* in the 16th century [27] (Figure 1).

Figure 1 - Lucas Cranach the Elder’s masterpiece Der Jungbrunnen (Fountain of Youth), painted in the 16th century European Renaissance. [27]



With the development of modern medicine, one of the best-known biological indicators of old age is the shortening of telomeres which protect the ends of chromosomes and the integrity of our DNA [38]. It is thought to be the cause of many age-related neurodegenerative and cardiovascular diseases, cancers, and other immunocompromising conditions. Shortening telomeres is a crucial area of interest for the field of medical space science. Excessive exposure to cosmic radiation, which astronauts are subject to, has been shown to shorten telomeres [38] in addition to the other detriments of space on the human body (e.g. decreased bone density [39], psychological isolation [40] etc.). The effects of radiation on the human genome were identified as early as 1927 by American geneticist Hermann Joseph Mueller for which he won the 1946 Nobel Prize in Physiology and Medicine [41].

NASA public research archives contain studies on radiation shortening of telomeres published from 2006-2020. In space, astronauts are exposed to bombardment by high energy HZE ions, high linear energy transfer (LET) recoil nuclei, and several other subatomic particles [42]. In a 2006 study of the cancer risks imposed by extended human space travel, Professor Francis A. Cucinotta, and renowned medical physicist, Marco Durante, write that, “In traveling to Mars, every cell nucleus within an astronaut would be traversed by a proton or secondary electron every few days, and an HZE ion about once per month” [42]. They remark that the substantial ionization power of the HZE ions make them heavy contributors to the cancer-risk of extended space travel.

From 2015-2017, professor of radiation cancer biology and oncology at Colorado State University, Susan Bailey’s research team measured telomere samples of 10 astronauts pre- and post- flight and compared them to age/sex matched individuals on Earth [60]. Additionally, they performed similar measurements on astronaut Scott Kelly as part of NASA’s One-Year Mission and Twins study. In the One-Year Mission, American Scott Kelly and Russian Mikhail Kornienko spent a full year from March of 2015 to March of 2016 on the International Space Station (ISS) [43] (Figure 2). The typical length of time spent on the ISS is six months, so the One-Year Mission was a momentous step towards understanding the long-term biological effects of space. The Twins study involved Scott Kelly and his identical twin Mark Kelly who remained on Earth (Figure 3). This study collected mass amounts of data on both twins and found that the human body, while affected by space travel, was surprisingly resilient. Within six months of returning to Earth, 91.3% of Scott’s gene expression levels had returned to normal [44]. While in space, Scott also received a flu vaccination with no additional complications. The full results of Bailey’s telomere study were not publicly reported, but in measuring the telomeres of Scott Kelly before, during, and after the One-Year Mission, it was shown that his telomeres actually lengthened during his time in space and shortened once he returned to Earth [45]. Prior to the year-long study, both twins had similar telomere lengths. It is not yet known why Scott’s telomeres exhibited this progression, but it certainly arouses some curiosity. Perhaps we will find that by mitigating some of the other biological, environmental, and psychological risks of space, a means to significantly extend human life from what we know now.

Figure 2 - Astronauts and identical twins Mark Kelly (left) and Scott Kelly (right). Both twins participated in NASA’s 2015-2016 Twins study. [57]

Figure 3 - A patch representing Kelly and Kornienko’s One-Year Mission on the International Space Station. [56]

Speculation aside, there are already real, existing implications to the astrophysical study of telomeres and radiation on terrestrial medicine. In 2015, Martin Kroupa (PhD) and co-authors published a paper which described a radiation environment monitor (REM) for space radiation dosimetry [46] (Figure 4A). The device was mounted on a USB device (Figure 4B) and sent for technological evaluation on the ISS. One of the REM was used over a 90-day period from November of 2014 to January of 2015 to verify the documented South Atlantic Anomaly. This is an area over Brazil which shows higher levels of radiation because of imbalances in the Earth's magnetic field [Source]. The results of this study by the REM are shown in Figure 4C. On Earth, the group is reportedly using this technology to develop the first personal radiation dosimeter [47]. This would be valuable for astronauts hoping to monitor their radiation levels in space, but it is dually important for cancer patients, X-ray recipients and operators, and nuclear power plant workers and researchers to better mitigate radiation risk.

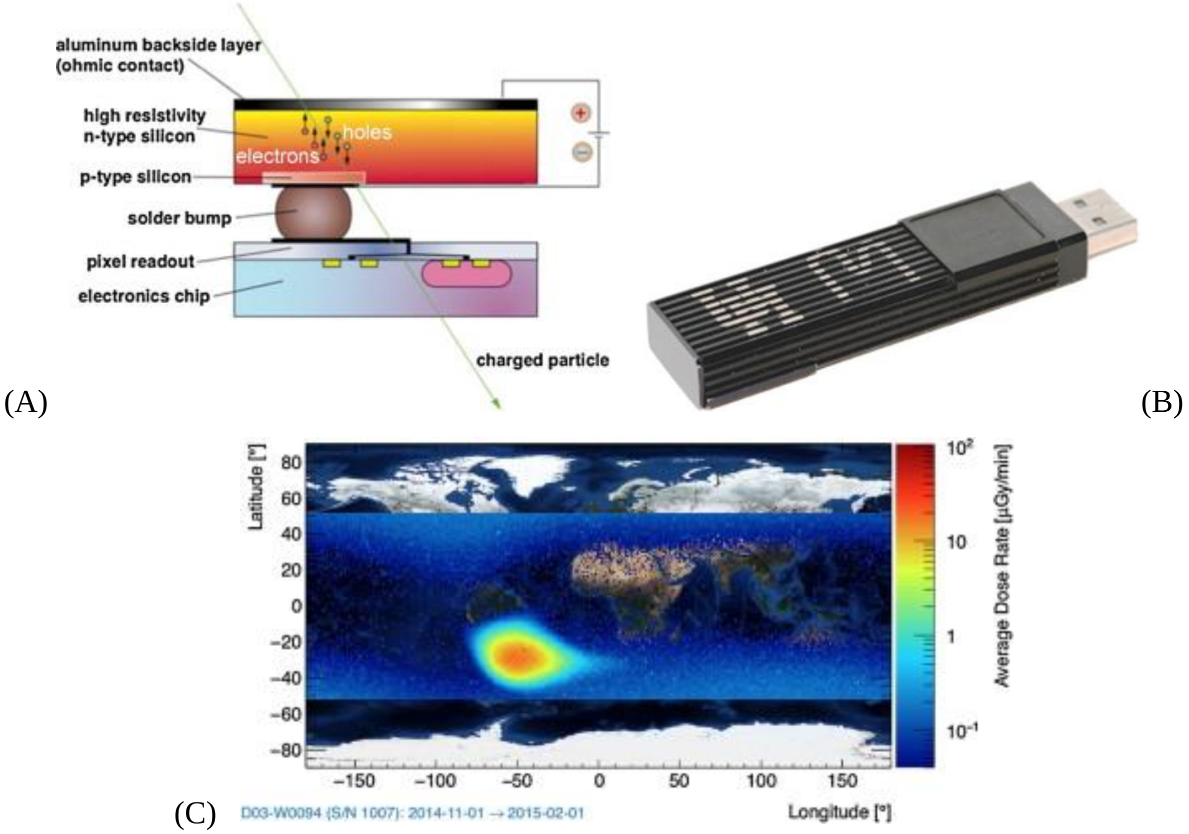


Figure 4 - A combination of images from Kroupa et al. research on radiation environment monitors (REM) for space radiation dosimetry. (A) depicts the operating components of the REM, while (B) shows the final integration of this technology into a USB. (C) shows the results of verifying the REM technology with the known South Atlantic Radiation Anomaly above Brazil. [46]

In addition to radiation research, space exploration has made substantial strides in the treatment of Alzheimer's disease and other neurodegenerative disorders. Alzheimer's disease does not have a known cause, but it is correlated with high levels of the protein beta-amyloid [48]. This protein is naturally occurring but damages neurons when it builds up excessively in the brain. The microgravity environment has allowed NASA scientists to study the fluidics of this protein without interference of surface interactions in the Ring Sheared Drop (RSD) project [49]. In the initial experiment, fluid was suspended between two tubes by its surface tension (Figure 5). One tube has the capability to rotate, creating a shear force within the protein solution. By learning more about this shear force, scientists hope that it will be possible to make inferences about how the beta-amyloid protein buildups might be removed from the brain without damaging the fragile biological environment. This is only one example, but it is exemplative of the potential for medical advancement which is exclusive to the space environment.

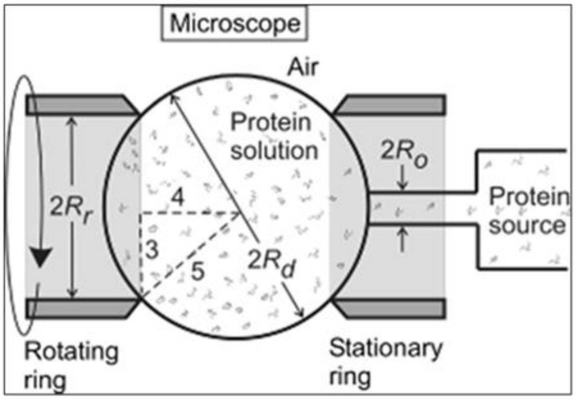


Figure 5 - The experimental setup of the Ring Sheared Drop Experiment at NASA. A drop of protein solution is suspended by its surface tension and two rings. One ring rotates to allow potential to measure shear stress on the protein solution. [49]

5.2 Helium 3

In recent years several groups globally including the NASA [74], the European Space Agency (ESA) [61], The Chinese Space Agency [66], and the Indian Space Resource Organization (ISRO) [72], have all turned towards a return to the Moon. A substantial reason for this interest is the promise of a clean and efficient fusion fuel, Helium-3. This is not a new discovery. As early as 1994, a fifty-year survey on Helium-3 research was published and remarked on the recent surge of interest in this light, non-radioactive isotope (Figure 6).

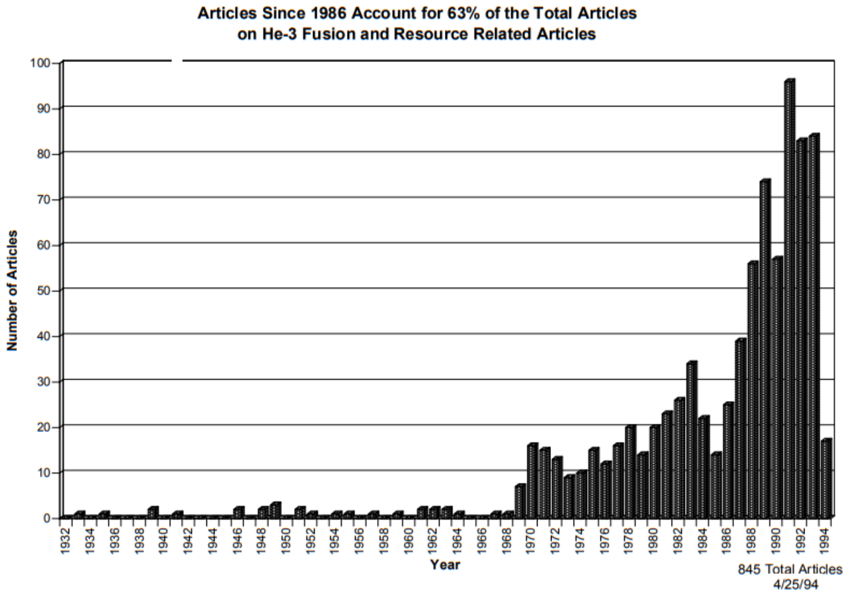


Figure 6 – Articles published regarding Helium-3 research from the years 1932-1994. There is a clear peak in interest following the 1970s when the Moon-landing took place. [62]

Fusion energy is what powers the greatest energy source known to us—the Sun. In fusion two lighter particles combine under extreme temperatures and pressure to form a larger particle and discard excess mass. This mass is discarded as energy which we seek to harness. While fusion energy production is not a reality yet, it is rapidly approaching. Nature writer Jeff Tolleson writes that as of December 2022, “Lawrence Livermore National Laboratory (LLNL) in California, has unequivocally achieved its goal of ignition in four out of its last six attempts, creating a reaction that generates pressures and temperatures greater than those that occur inside the Sun” [68]. Fusion notably does not produce harmful environmental emissions and very little long-lasting nuclear waste [69].

Alternative to any use of Helium-3 is the deuterium-tritium (DT) or deuterium-deuterium fusion reactions. In both reactions, the particles are fused and produce impressive amounts of energy, however they have the biproduct of high energy neutrons (Figure 7) [62]. These neutrons cause a lot of wear to equipment, produce a greater amount of nuclear waste, and misdirect a lot of the reaction’s energy potential. Using Helium-3 in either Deuterium-Helium or Helium-Helium reactions nearly eliminates this issue. These reactions produce instead a high energy proton which, through use of electrostatic Direct Energy Converters (DEC), can be converted into energy as well [62]. Deuterium-Helium reactions do have a secondary process which produces these neutrons, but it is less than 1% of energy from the reactor in most cases [62]. However, Helium-4 makes up only about 5.2 parts per million of the Earth's atmosphere and

Helium-3 makes up even less [70]. As a result, when an abundance of Helium-3 was discovered in samples from the Moon-landing, it was instantly a point of interest in our sustainable future.

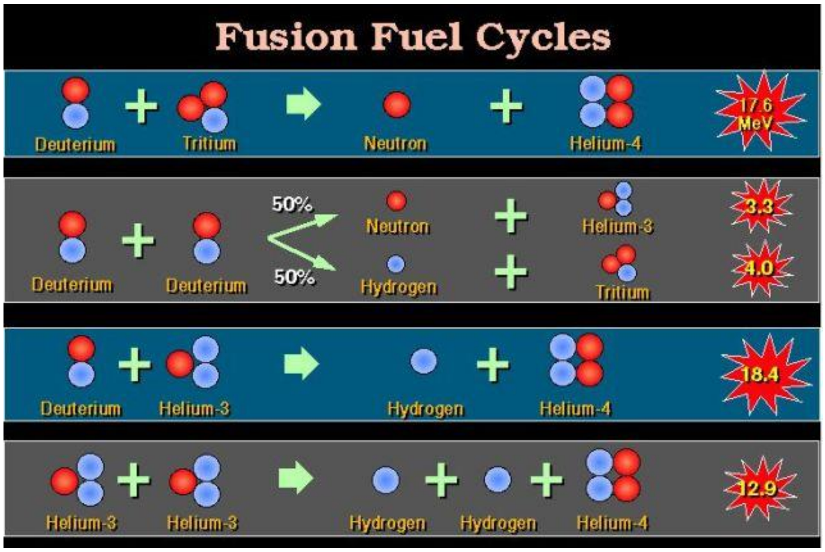


Figure 7 – Types of fusion and their energy production in mega-electronvolts [MeV]. The figure shows four types of reactions involving Deuterium, Tritium, and Helium-3. Reactions without Helium-3 produce high energy destructive neutrons. [70]

Just as Helium-3 is interesting however, it is also a point of global contention. From 1979-1984, 19 countries (Armenia, Australia, Austria, Belgium, Chile, Kazakhstan, Kuwait, Lebanon, Mexico, Morocco, Netherlands, Pakistan, Peru, Philippines, Saudi Arabia, Turkey, Uruguay, and Venezuela) signed and ratified Moon agreement [73]; an agreement governing activities on the Moon and other celestial bodies. Within this agreement it was stated that,

> The Moon and its natural resources are the common heritage of mankind. The Moon is not subject to national appropriation by any claim of sovereignty, by means of use or occupation, or by any other means. Neither the surface nor the subsurface of the Moon, nor any part thereof or its natural resources, can become the property of any State, international intergovernmental or non-governmental organization, national organization or non-governmental entity, or of any natural person [63].

This would clearly bar the use of Helium-3 from any economic activities of a singularly acting organization of government. However, if we return to the countries which have expressed the most interest by their publications in the 1994 survey of Helium-3 research, the United States makes up 60% of the publications, followed by Japan, and Russia [62]. Notably, none of these countries have signed or ratified the Moon agreement. It is not until Austria, after Russia, that there is an intersection between these lists. This makes sense as far as countries protecting their initiatives, however with such a valuable resource on the line, it is potentially foreboding for global relations if those most actively pursuing Helium-3 are not equivalently involved in the discussion around conservation of the Moon's heritage, resources, and ownership. Helium-3, if not used at all, would be a devastating waste of scientific potential. Perhaps, though, considering the Moon's other extremely valuable and unique attributes-- its environmental role on Earth, its proximity allowing for a scientific outpost, in combination with its thin atmosphere allowing for clear observation-- it could be used to first explore and understand the expanse of resources available to us in other places or in other forms.

6 Transportation

A necessary consideration to maximizing the humanitarian potential of space exploration, is ensuring the sustainability of transportation methods from both an environmental and economic perspective. Actual mission planning on this scale can take decades, however, in the interest of exploring potential propulsion options in their complexity within our given time frame, it is in our interest to simplify this process to the most crucial elements of a potential mission. In the following section, we set the mission goal of having a continuous orbit between the Earth and a lunar outpost with the ability to make rendezvous with a lunar ISS. We discuss what is required of a propulsion method in terms of thrust and impulse based on sample orbital plans (section 6.1). Discussing a variety of heritage chemical propulsion methods, electric propulsion methods, and other novel methods or propulsion aids (e.g. solar sails), we make a proposal for which may be most suited to our mission (section 6.3).

6.1 Thrust & Impulse Requirements

6.1a Orbital Parameters

We begin our in-space mission in what is known as Low Earth Orbit (LEO). Low Earth Orbit describes any orbit with an altitude of ≤ 2,000 km [50]. From this measurement, we can begin to describe the orbit by its parameters which prove useful in later calculations. These parameters include apogee and perigee radii, eccentricity, period, and angular momentum. Since our mission is eventually concerned with exiting the initial orbit, we propose an altitude of 2,000 km to most closely near this goal. The apogee r_a and perigee r_p radii of the starting orbit are measured from the Earth's center of mass. Assuming a circular starting orbit, we calculate the apogee and perigee radii jointly as the sum of altitude and Earth's radius (approximately 6,378 km [51]); this gives us r_a, r_p = 9,378 km. The eccentricity e of the orbit can be calculated by equation (1) [52]. Since we assume a circular orbit, the magnitude of eccentricity for our initial orbit is zero.

$$e = \frac{r_a - r_p}{r_a + r_p} \tag{1}$$

The period of an orbit is given by (2) [52], such that a is the semi-major axis of the ellipse, and μ is the standard gravitational parameter of the governing gravitational body. μ is approximately equal to the product of the gravitation constant G ($6.67 \cdot 10^{-20}$ N·km^2/kg^2) with the governing mass M. ($M_e = 5.97 \cdot 10^{24}$ kg, mass of Earth).

$$T = \frac{2\pi}{\sqrt{\mu}} \cdot a^{\frac{3}{2}} \tag{2}$$

Earth's standard gravitational parameter is μ = 398,200 N·km^2/kg^2. For our circular orbit, the semi-major axis is the value of $r_a = r_p$ = 9,378 km, thus giving it a period of 9,038 seconds. For any elliptical (or circular) orbit, the radius r of the object from its focal point (the center for a circular orbit) is represented by the orbit equation (3) [52].

$$r = \frac{h^2}{\mu} \frac{1}{1 + e\cos\theta} \tag{3}$$

Where h is the angular momentum of the orbit, and θ is the true anomaly formed between the position vector $\vec{r}$ and the eccentricity vector $\vec{e}$ parallel to apse line. Inputting the perigee radius for r and the corresponding anomaly $\theta = 0$ rad, we can solve for the remaining variable h to get the angular momentum of the orbit (4).

$$h = \sqrt{r_p \cdot \mu(1 + e)} \tag{4}$$

The angular momentum of an orbit is a constant value, a property which follows from Kepler's law of equal areas [52]. Solving for the angular momentum of our initial orbit gives us 61,140 km^{2}s^{-1}.

The next orbit we consider is the Moon's orbit about earth. For this, the apogee and perigee radius, eccentricity, angular momentum, and period are all given in NASA's Moon Factsheet [53]. These values are represented in Table 1 below.

Table 1. Orbital parameters of LEO and lunar orbit about Earth.

Orbital Parameters	**LEO**	**Moon (rel. Earth)**
Apogee r_a [km]	9,378	405,500
Perigee r_p [km]	9,378	363,300
Eccentricity, e	0.000	0.05489
Angular momentum, h [$\mathrm{kg \cdot km^2 \cdot s^{-1}}$]	61,140	390,800
Period, T [s]	9,038	2,371,000

The final orbit we consider is our halfway-destination orbit about the Moon. In our sample problem, we choose an orbital radius of 6,000 km, well-within the Moon's sphere of influence [54]. The parameters of such an orbit are depicted in Table 2.

Table 2. Orbital parameters of the lunar-centric orbit (sample problem).

Orbital Parameters	**Lunar-Centric Orbit**
Apogee r_a [km]	6,000
Perigee r_p [km]	6,000
Eccentricity, e	0.000
Angular momentum, h [$\mathrm{kg \cdot km^2 \cdot s^{-1}}$]	5,424
Period, T [s]	41,700

We are now fully equipped to begin calculating the impulse required for successive orbital maneuvers.

6.1b Orbital Maneuvers

A Hohmann transfer orbit is the most efficient two-impulse maneuver to travel between two orbits with a common focus [52]. It is multidirectional and is defined tangential to both orbits along their common apse-line. The impulse maneuvers which comprise the Hohmann transfer can be approximated by instantaneous changes in velocity at the points of transfer.

The apse-line of an orbit is defined in the direction of its eccentricity vector (or along the semimajor axis of an ellipse). When transferring from a circular LEO to the Moon's orbit about

Earth, the common apse line coincides with the apse line of the Moon's orbit about Earth. The perigee of a simple transfer orbit would be located at the intersection of this apse line with the initial orbit, and the apogee would be coincident with that of the Moon's. This puts a satellite into a collision course with the Moon as it reaches apogee. To enter orbit around the Moon from our transfer orbit we make a minor adjustment by defining the apogee of the transfer orbit not precisely coincident with the Moon's orbit but further out by our chosen orbiting radius (6,000 km). By choosing a launch window such that the satellite coincides with Moon at their respective apogee points, the satellite will be within the Moon's sphere of influence where an impulsive maneuver can be performed to capture it in lunar orbit. The orbital parameters of the Hohmann transfer orbit described are depicted in Table 3. This denotes the first maneuver.

Table 3. Orbital parameters of the departing Hohmann transfer orbit (sample problem).

Orbital Parameters	**Departing Hohmann Transfer**
Apogee r_a [km]	411,500
Perigee r_p [km]	9,378
Eccentricity, e	0.9554
Angular momentum, h [kg·km^2·s^{-1}]	85,500
Period, T [s]	949180

When choosing a propulsion method, the impulse requirement is given by the collective change in velocity required to execute each impulsive maneuver. For the first maneuver described above, we calculate the change in velocity by calculating the initial velocity at perigee in LEO and final velocity required to reach the orbital energy of the Hohmann transfer orbit at this same point. These velocities can be calculated by dividing the angular momentum of each orbit by the radius of perigee.

$$v_i = \frac{61140\ kgkm^2s^{-1}}{9378\ km} = 6.520\ kms^{-1} \tag{5}$$

$$v_f = \frac{85500\ kgkm^2s^{-1}}{9378\ km} = 9.117\ kms^{-1} \tag{6}$$

$$\Delta v_1 = 2.597\ kms^{-1} \tag{7}$$

This is the impulse required by the first maneuver.

The second maneuver will take place upon meeting with the Moon at its apogee. In the same manner as above, we can calculate the velocity of an object at both energy orbitals to get the impulse required to transfer into the lunar-centric orbit.

$$v_i = \frac{85500\ km^2s^{-1}}{411500\ km} = 0.2078\ kms^{-1} \tag{8}$$

$$v_f = \frac{5424\ km^2s^{-1}}{6000\ km} = 0.9040\ kms^{-1} \tag{9}$$

$$\Delta v_2 = \ 0.6962\ kms^{-1} \tag{10}$$

Impulse calculations for the remaining orbital maneuvers follow in the next section. We need these calculations before coming to the total impulse requirement for our sample mission.

6.1c Departure Times

Upon reaching the lunar-centric fly-by orbit, suppose that we would like to orbit the Moon three times before planning our return, such as to rendezvous with a lunar ISS. Since the duration of time spent in orbit around the Moon affects the true anomaly of the Moon in its orbit around Earth, it also determines the tilt axis of our returning Hohmann transfer. Multiplying the orbital period by three, we are given that the return time of the spacecraft must be 125,100 seconds past the Moon's apogee. To obtain the axis tilt from this value, we must know precisely where the Moon is in its orbit at this time. To do this, we first calculate the mean anomaly M_a of the Moon at the given time (8). The mean anomaly is defined in Oxford's reference dictionary as, "The angle between the periapsis of an orbit and the position of an imaginary body that orbits in the same period as the real one but at a constant angular speed" [55].

$$M_a = \frac{2\pi}{T}t \tag{8}$$

For $t = 131{,}100$ (125,100 s added to half the Moon's orbital period),

$$M_a = 3.473\ rad \tag{9}$$

The mean anomaly is related to the eccentric anomaly E by equation (10).

$$M_a = E - e\sin(E) \tag{10}$$

The eccentric anomaly is the angle of an object from periapsis as it is projected onto a circumscribing concentric circle around the ellipse with the same radius as the ellipse's semimajor axis (Figure 8). Since the equation in (10) is non-invertible, we must approximate the corresponding eccentric anomaly by Newton's method (or another method of mathematical approximation). The resulting eccentric anomaly is $E = 3.456\ rad$.

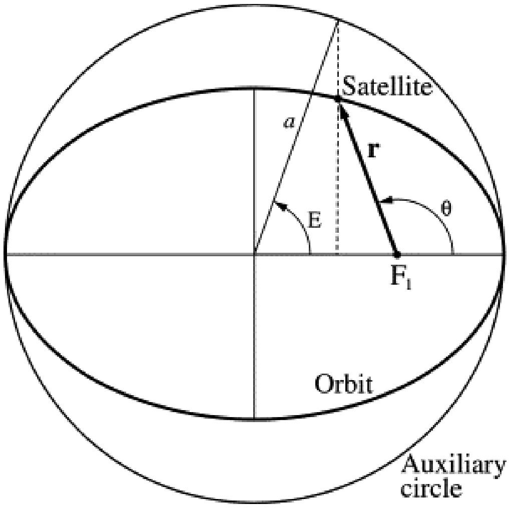


Figure 8 - An auxiliary circle demonstrating the difference between eccentric and true anomaly of a satellite in elliptical orbit. [58]

At last, we may calculate the true anomaly from the eccentric anomaly using (11).

$$\theta = \cos^{-1}\left(\frac{e-\cos E}{e\cos E-1}\right) \tag{11}$$

The true anomaly of the Moon after three lunar orbits of the spacecraft is $\theta = -2.844\ rad$ or approximately 197°. From equation (3), we can deduce that the radius of the Moon to Earth is approximately 404,480 km at this time. This value is critical in calculating the orbital parameters of the return transfer. Accommodating for another 9378-altitude orbit around Earth upon return, the orbital parameters of the return transfer are shown in Table 4.

Table 4. Orbital parameters of the returning Hohmann transfer orbit (sample problem).

Orbital Parameters	**Returning Hohmann Transfer**
Apogee r_a [km]	410,480
Perigee r_p [km]	9,378

Eccentricity, *e*	0.9553
Angular momentum, *h* [kg·km^2·s^{-1}]	85,490
Period, *T* [s]	957,200

**As we would expect, the departing and returning Hohmann transfers have similar parameter values.*

In the same manner as before, we can calculate the impulse required to leave lunar-centric orbit, and then to re-enter geo-centric orbit.

Leaving lunar-centric orbit:

$$v_i = \frac{5424\ kgkm^2s^{-1}}{6000\ km} = 0.9040\ kms^{-1} \tag{11}$$

$$v_f = \frac{85490\ kgkm^2s^{-1}}{410480\ km} = 0.2083\ kms^{-1} \tag{12}$$

$$\Delta v_3 = \ -0.6957\ kms^{-1} \tag{13}$$

Re-entering LEO:

$$v_i = \frac{85490\ kgkm^2s^{-1}}{9378\ km} = 9.116\ kms^{-1} \tag{14}$$

$$v_f = \frac{61140\ kgkm^2s^{-1}}{9378\ km} = 6.520\ kms^{-1} \tag{15}$$

$$\Delta v_4 = \ -2.597\ kms^{-1} \tag{16}$$

Both maneuvers have negative impulse, meaning that the spacecraft will need to decelerate to enter the proper energy orbital. Adding the absolute value of all four maneuvers together, we have the total delta-v for our proposed mission (17),

$$\Delta v = 6.586\ kms^{-1} \tag{17}$$

This is the impulse requirement of our mission, but specific impulse will depend on the type of fuel used as described in later sections (Section 6.2).

6.1d Simulation

A MATLAB simulation of our proposed mission was compiled as an educational resource and a visual aid to the orbital mechanics of section 6.1. The simulation operates on the same mathematical principles demonstrated in section 6.1 and the corresponding code is referenced in Appendix A.

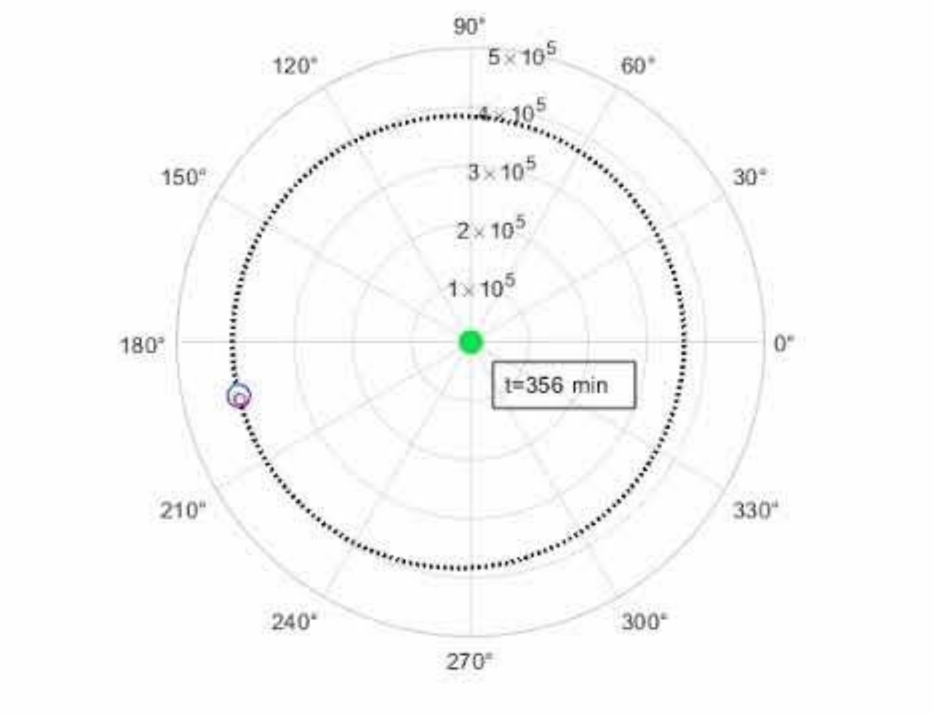


Figure 9 - MATLAB simulation of the proposed orbital plan for a maintenance ship sent to rendezvous with a lunar outpost or ISS. The Earth is denoted in green, the Moon in blue, and the spacecraft in red.

6.2 Propulsion Methods & Propellants

The ideal propulsion system is reliable, requires minimal maintenance, and has propellent that is cheap, easy to obtain, and produces a high specific impulse, meaning it is efficient for its weight. In this section we will outline the different options for propellants and propulsion systems and what applications they would be used best in to determine the optimal methods for our proposed mission.

The rocket thrust equation is defined as the mass flow rate (mdot) times the equivalent velocity (V_{eq})

$$F = mdot * Veq$$

The total impulse (I) of a rocket is defined as the average thrust (F) times the total time of firing (Δt).

$$I = F * \Delta t$$

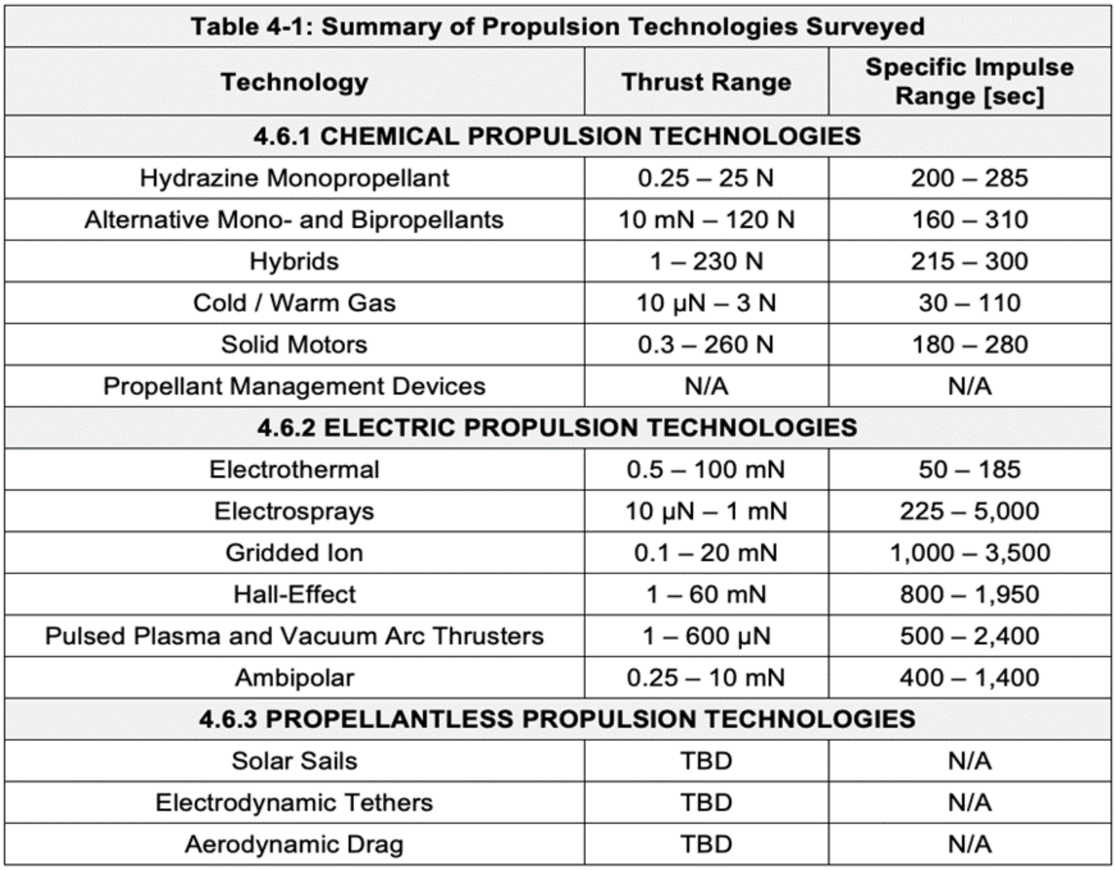


Table 4-1: Summary of Propulsion Technologies Surveyed		
Technology	**Thrust Range**	**Specific Impulse Range [sec]**
4.6.1 CHEMICAL PROPULSION TECHNOLOGIES		
Hydrazine Monopropellant	0.25 – 25 N	200 – 285
Alternative Mono- and Bipropellants	10 mN – 120 N	160 – 310
Hybrids	1 – 230 N	215 – 300
Cold / Warm Gas	10 μN – 3 N	30 – 110
Solid Motors	0.3 – 260 N	180 – 280
Propellant Management Devices	N/A	N/A
4.6.2 ELECTRIC PROPULSION TECHNOLOGIES		
Electrothermal	0.5 – 100 mN	50 – 185
Electrosprays	10 μN – 1 mN	225 – 5,000
Gridded Ion	0.1 – 20 mN	1,000 – 3,500
Hall-Effect	1 – 60 mN	800 – 1,950
Pulsed Plasma and Vacuum Arc Thrusters	1 – 600 μN	500 – 2,400
Ambipolar	0.25 – 10 mN	400 – 1,400
4.6.3 PROPELLANTLESS PROPULSION TECHNOLOGIES		
Solar Sails	TBD	N/A
Electrodynamic Tethers	TBD	N/A
Aerodynamic Drag	TBD	N/A

Figure 10 – Thrust vs Specific Impulse of Different Fuels [2]

To find the specific impulse (I_{sp}) in seconds, the impulse can be divided by the mass of the propellants times the gravitational acceleration constant (g_0). This can be simplified to the following equation.

$$Isp = F/mdot * g0$$

The I_{sp} is a ratio of the thrust produced to the weight flow of the propellants. The I_{sp} "is an indication of engine efficiency. Two different rocket engines have different values of specific impulse. The engine with the higher value of specific impulse is more efficient because it produces more thrust for the same amount of propellant." [1]

6.2a Chemical propulsion

"Chemical propulsion systems are designed to satisfy high-thrust impulsive maneuvers. They offer lower specific impulse compared to their electric propulsion counterparts but have significantly higher thrust to power ratios” [2]. For these reasons, they typically would not be used as the primary propellent for long-term missions but are useful for launching the rocket from Earth into orbit and for use as supplementary propulsion when short, high thrust maneuvers are necessary. For this reason, we are not primarily focused on them for long distance travel or for continuous use on an orbiting Moon base.

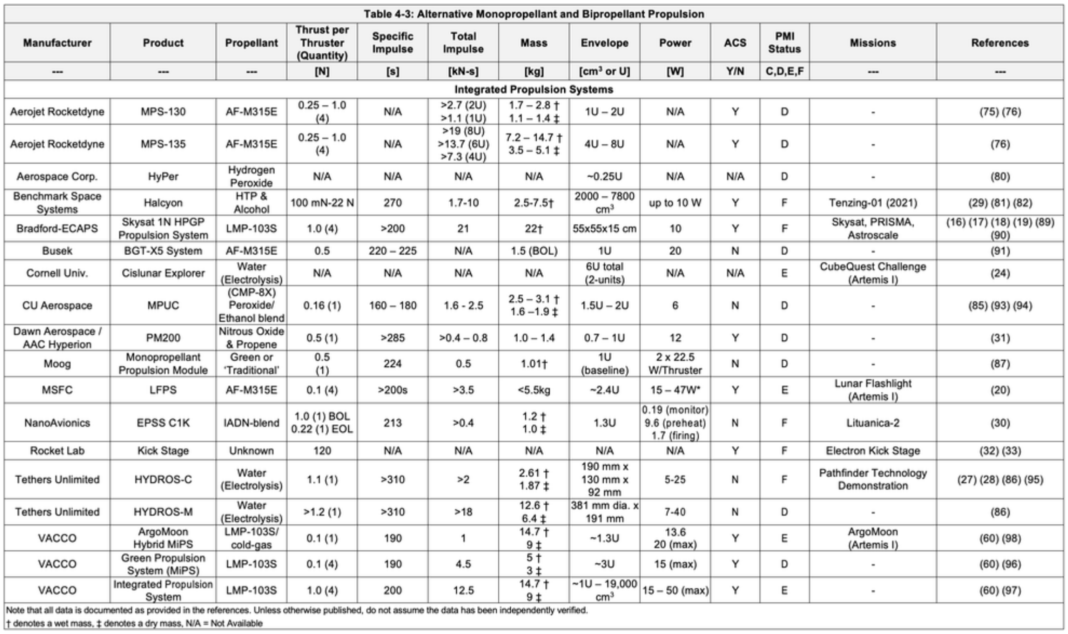


Table 4-3: Alternative Monopropellant and Bipropellant Propulsion

Manufacturer	Product	Propellant	Thrust per Thruster (Quantity)	Specific Impulse	Total Impulse	Mass	Envelope	Power	ACS	PMI Status	Missions	References
---	---	---	[N]	[s]	[kN-s]	[kg]	[cm^3 or U]	[W]	Y/N	C,D,E,F	---	---
Integrated Propulsion Systems												
Aerojet Rocketdyne	MPS-130	AF-M315E	0.25 – 1.0 (4)	N/A	>2.7 (2U) >1.1 (1U)	1.7 – 2.8 † 1.1 – 1.4 ‡	1U – 2U	N/A	Y	D	-	(75) (76)
Aerojet Rocketdyne	MPS-135	AF-M315E	0.25 – 1.0 (4)	N/A	>19 (8U) >13.7 (6U) >7.3 (4U)	7.2 – 14.7 † 3.5 – 5.1 ‡	4U – 8U	N/A	Y	D	-	(76)
Aerospace Corp.	HyPer	Hydrogen Peroxide	N/A	N/A	N/A	N/A	~0.25U	N/A	N/A	D	-	(80)
Benchmark Space Systems	Halcyon	HTP & Alcohol	100 mN-22 N	270	1.7-10	2.5-7.5†	2000 – 7800 cm^3	up to 10 W	Y	F	Tenzing-01 (2021)	(29) (81) (82)
Bradford-ECAPS	Skysat 1N HPGP Propulsion System	LMP-103S	1.0 (4)	>200	21	22†	55x55x15 cm	10	Y	F	Skysat, PRISMA, Astroscale	(16) (17) (18) (19) (89) (90)
Busek	BGT-X5 System	AF-M315E	0.5	220 – 225	N/A	1.5 (BOL)	1U	20	N	D	-	(91)
Cornell Univ.	Cislunar Explorer	Water (Electrolysis)	N/A	N/A	N/A	N/A	6U total (2-units)	N/A	N/A	E	CubeQuest Challenge (Artemis I)	(24)
CU Aerospace	MPUC	(CMP-8X) Peroxide/ Ethanol blend	0.16 (1)	160 – 180	1.6 - 2.5	2.5 – 3.1 † 1.6 –1.9 ‡	1.5U – 2U	6	N	D	-	(85) (93) (94)
Dawn Aerospace / AAC Hyperion	PM200	Nitrous Oxide & Propene	0.5 (1)	>285	>0.4 – 0.8	1.0 – 1.4	0.7 – 1U	12	Y	D	-	(31)
Moog	Monopropellant Propulsion Module	Green or 'Traditional'	0.5 (1)	224	0.5	1.01†	1U (baseline)	2 x 22.5 W/Thruster	N	D	-	(87)
MSFC	LFPS	AF-M315E	0.1 (4)	>200s	>3.5	<5.5kg	~2.4U	15 – 47W*	Y	E	Lunar Flashlight (Artemis I)	(20)
NanoAvionics	EPSS C1K	IADN-blend	1.0 (1) BOL 0.22 (1) EOL	213	>0.4	1.2 † 1.0 ‡	1.3U	0.19 (monitor) 9.6 (preheat) 1.7 (firing)	N	F	Lituanica-2	(30)
Rocket Lab	Kick Stage	Unknown	120	N/A	N/A	N/A	N/A	N/A	Y	F	Electron Kick Stage	(32) (33)
Tethers Unlimited	HYDROS-C	Water (Electrolysis)	1.1 (1)	>310	>2	2.61 † 1.87 ‡	190 mm x 130 mm x 92 mm	5-25	N	F	Pathfinder Technology Demonstration	(27) (28) (86) (95)
Tethers Unlimited	HYDROS-M	Water (Electrolysis)	>1.2 (1)	>310	>18	12.6 † 6.4 ‡	381 mm dia. x 191 mm	7-40	N	D	-	(86)
VACCO	ArgoMoon Hybrid MiPS	LMP-103S/ cold-gas	0.1 (1)	190	1	14.7 † 9 ‡	~1.3U	13.6 20 (max)	Y	E	ArgoMoon (Artemis I)	(60) (98)
VACCO	Green Propulsion System (MiPS)	LMP-103S	0.1 (4)	190	4.5	5 † 3 ‡	~3U	15 (max)	Y	D	-	(60) (96)
VACCO	Integrated Propulsion System	LMP-103S	1.0 (4)	200	12.5	14.7 † 9 ‡	~1U – 19,000 cm^3	15 – 50 (max)	Y	E	-	(60) (97)

Note that all data is documented as provided in the references. Unless otherwise published, do not assume the data has been independently verified.
† denotes a wet mass, ‡ denotes a dry mass, N/A = Not Available

Figure 11 - Properties of Different Chemical Fuels [2]

6.2b Electric propulsion

Electric propulsion typically offers significantly higher specific impulse compared to chemical propulsion. This comes at the expense of lower thrust-to-power levels, however, meaning electric propulsion cannot output thrust quickly and needs to operate for far longer to produce the same amount of total impulse. Electric propulsions high impulse makes it ideal for maintaining orbit for our proposed lunar orbital base or for long term missions to places like Mars where its lack of thrust is not a significant issue or can be compensated for in other ways. [2].

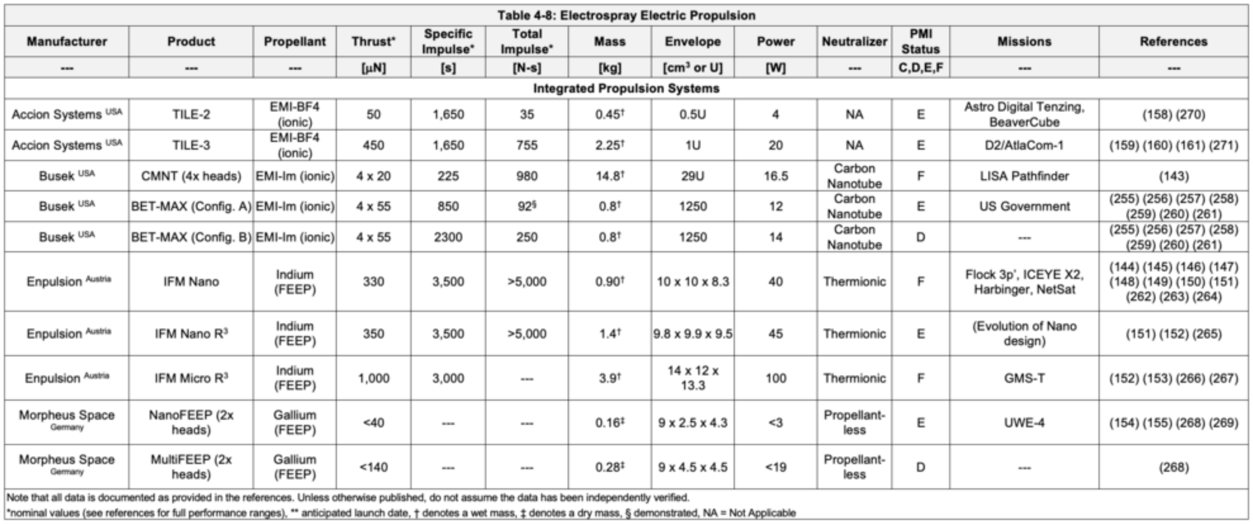


Table 4-8: Electrospray Electric Propulsion

Manufacturer	Product	Propellant	Thrust*	Specific Impulse*	Total Impulse*	Mass	Envelope	Power	Neutralizer	PMI Status	Missions	References
---	---	---	[µN]	[s]	[N-s]	[kg]	[cm^3 or U]	[W]	---	C,D,E,F	---	---
Integrated Propulsion Systems												
Accion Systems ^{USA}	TILE-2	EMI-BF4 (ionic)	50	1,650	35	0.45†	0.5U	4	NA	E	Astro Digital Tenzing, BeaverCube	(158) (270)
Accion Systems ^{USA}	TILE-3	EMI-BF4 (ionic)	450	1,650	755	2.25†	1U	20	NA	E	D2/AtlaCom-1	(159) (160) (161) (271)
Busek ^{USA}	CMNT (4x heads)	EMI-Im (ionic)	4 x 20	225	980	14.8†	29U	16.5	Carbon Nanotube	F	LISA Pathfinder	(143)
Busek ^{USA}	BET-MAX (Config. A)	EMI-Im (ionic)	4 x 55	850	92§	0.8†	1250	12	Carbon Nanotube	E	US Government	(255) (256) (257) (258) (259) (260) (261)
Busek ^{USA}	BET-MAX (Config. B)	EMI-Im (ionic)	4 x 55	2300	250	0.8†	1250	14	Carbon Nanotube	D	---	(255) (256) (257) (258) (259) (260) (261)
Enpulsion ^{Austria}	IFM Nano	Indium (FEEP)	330	3,500	>5,000	0.90†	10 x 10 x 8.3	40	Thermionic	F	Flock 3p', ICEYE X2, Harbinger, NetSat	(144) (145) (146) (147) (148) (149) (150) (151) (262) (263) (264)
Enpulsion ^{Austria}	IFM Nano R^3	Indium (FEEP)	350	3,500	>5,000	1.4†	9.8 x 9.9 x 9.5	45	Thermionic	E	(Evolution of Nano design)	(151) (152) (265)
Enpulsion ^{Austria}	IFM Micro R^3	Indium (FEEP)	1,000	3,000	---	3.9†	14 x 12 x 13.3	100	Thermionic	F	GMS-T	(152) (153) (266) (267)
Morpheus Space Germany	NanoFEEP (2x heads)	Gallium (FEEP)	<40	---	---	0.16‡	9 x 2.5 x 4.3	<3	Propellant-less	E	UWE-4	(154) (155) (268) (269)
Morpheus Space Germany	MultiFEEP (2x heads)	Gallium (FEEP)	<140	---	---	0.28‡	9 x 4.5 x 4.5	<19	Propellant-less	D	---	(268)

Note that all data is documented as provided in the references. Unless otherwise published, do not assume the data has been independently verified.
*nominal values (see references for full performance ranges), ** anticipated launch date, † denotes a wet mass, ‡ denotes a dry mass, § demonstrated, NA = Not Applicable

Figure 12 - Properties of Different Fuels for Electrospray Propulsion [2]

6.2c Novel propulsion methods

Another proposed method of propulsion is Magnetic Fusion Plasma Engines (MFPE). They combine elements of fusion propulsion, ionic propulsion, and other concepts.

> "The MFPD is a propulsion system for space exploration, utilizing controlled nuclear fusion reactions as a primary energy source for both thrust and potential electric power generation. The system is predicated on harnessing the immense energy output from fusion reactions, typically involving isotopes of hydrogen or helium, to produce a high-velocity exhaust of particles, thereby generating thrust according to Newton's third law.” [59]

The advantage of the method is the fact it can provide thrust and power for the ship from a single energy source which could lessen, or eliminate, the need for solar panels on board thereby reducing the weight and fuel needed. MFPEs also produce a high specific impulse, use extremely energy dense fuels, have the possibility of using magnetic and physical structures of the propulsion system to shield from radiation, doesn’t depend on being close to a star, and minimizes the risk of radioactive contamination compared to nuclear-thermal or fission-electric concepts since it requires less radioactive material and may allow for a safer reactor shutdown.

The main challenges of MFPEs are the lack of research and practical tests on achieving stable fusion reactions in space, how it will handle the heat and radiation, and the possible need for neutron shielding in neutron heavy reactions to protect the crew and structural integrity of the craft. [6]

There is also the possibility of completely propellent-less propulsion, but it is typically either bulky or dependent on some external factor (ie solar sails) and would not be reliable or fast enough for long term travel. It can, however, be used as a supplement to fuel in the case of keeping a station or satellite in orbit to reduce the amount of fuel and in turn resupplies needed for continuous operation.

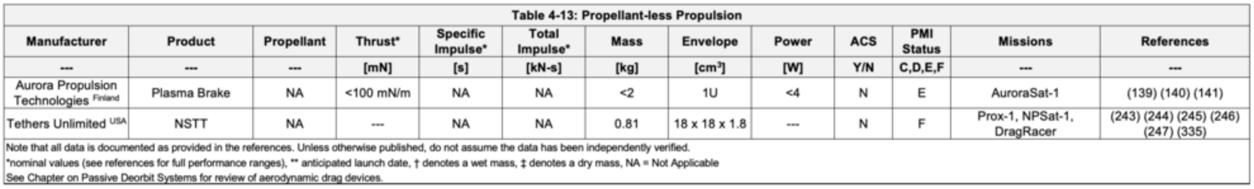


Table 4-13: Propellant-less Propulsion

Manufacturer	Product	Propellant	Thrust*	Specific Impulse*	Total Impulse*	Mass	Envelope	Power	ACS	PMI Status	Missions	References
---	---	---	[mN]	[s]	[kN-s]	[kg]	[cm³]	[W]	Y/N	C,D,E,F	---	---
Aurora Propulsion Technologies Finland	Plasma Brake	NA	<100 mN/m	NA	NA	<2	1U	<4	N	E	AuroraSat-1	(139) (140) (141)
Tethers Unlimited USA	NSTT	NA	---	NA	NA	0.81	18 x 18 x 1.8	---	N	F	Prox-1, NPSat-1, DragRacer	(243) (244) (245) (246) (247) (335)

Note that all data is documented as provided in the references. Unless otherwise published, do not assume the data has been independently verified.
*nominal values (see references for full performance ranges), ** anticipated launch date, † denotes a wet mass, ‡ denotes a dry mass, NA = Not Applicable
See Chapter on Passive Deorbit Systems for review of aerodynamic drag devices.

Figure 13 - Properties of Different Types of Propellent-less Propulsion [2]

Solar sails are possibly the most well-known method of propellent-less propulsion. They harness the energy of photons from stars using a very thin reflective sheet to produce thrust. The momentum of photons can be given by the following equation.

$$\rho = \frac{hv}{c}$$

Where h is Planck's constant, v is the frequency, and c is the speed of light.

The total pressure on the sail due to the photons can be given by this equation.

$$P\ (total) = \frac{(1 + R)\ Ix}{c}$$

Where R is a fraction between zero and one describing the constant reflectivity of the sails material and I_x is the light intensity which can be described by this equation.

$$Ix = \frac{K}{4\pi r^2}$$

Where K is the luminosity in watts of the star and r is the sail distance. [7]

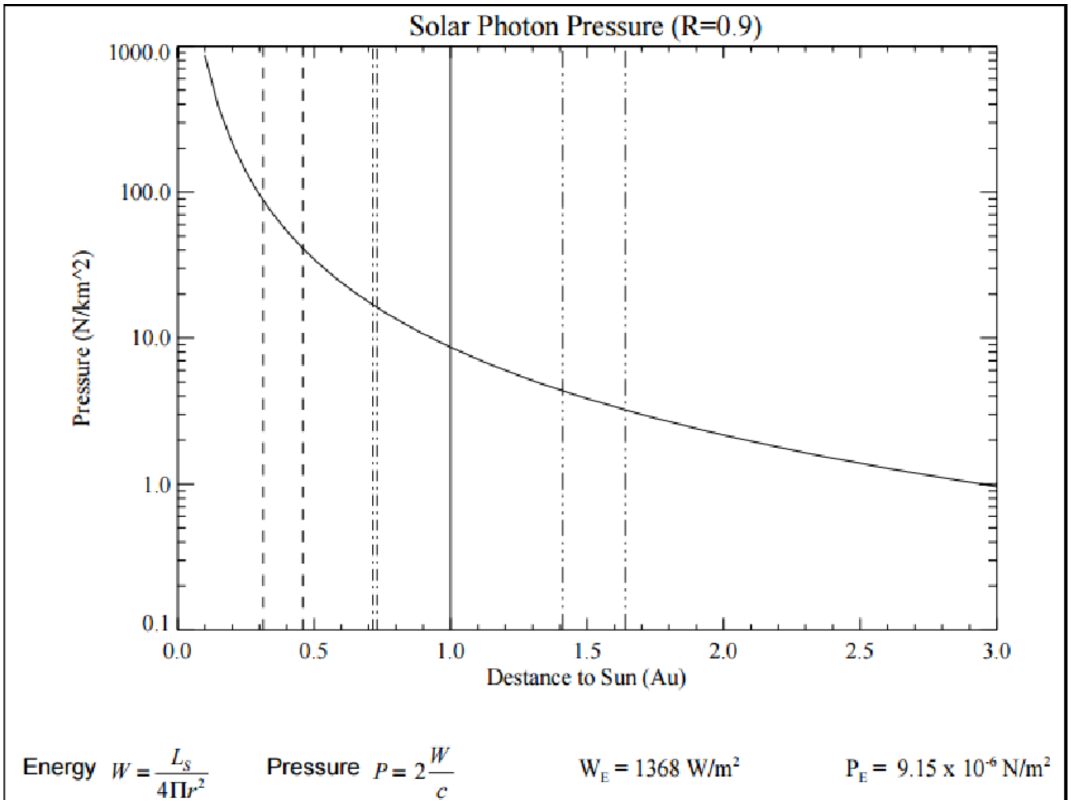


Figure 14 - Pressure on Solar Sail as Distance to the Sun Changes [8]

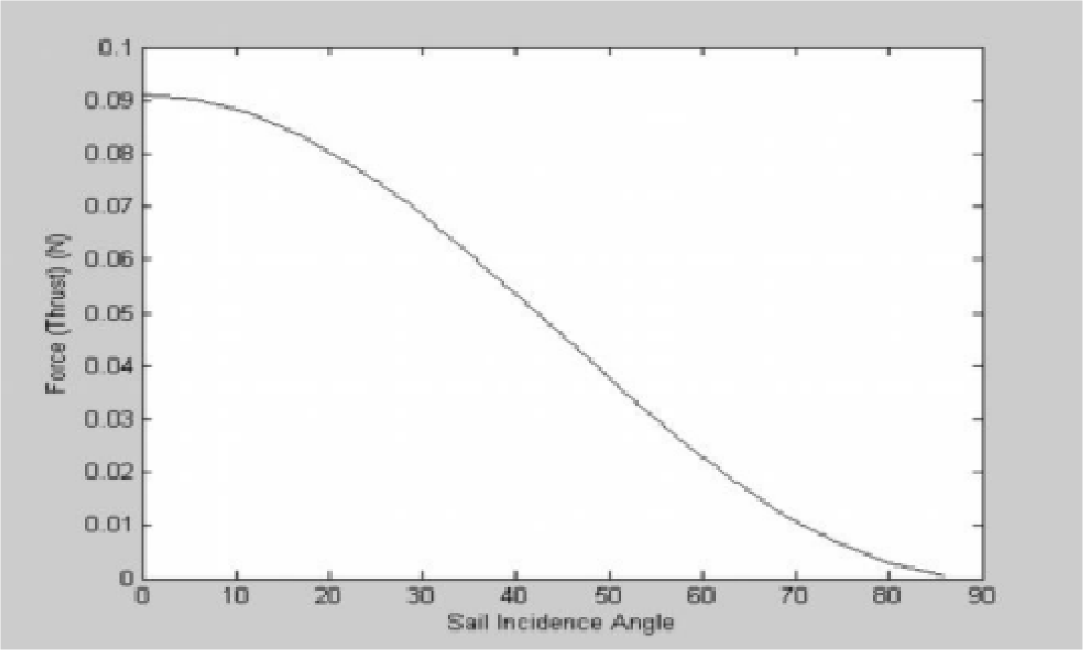


Figure 15 - Solar Sail Total Force (Thrust) Vs. Sun-Incidence Angle For a 100 x 100 meter perfect sail @ 1 A.U [8]

6.2d Estimated Cost and Times of Use

For long term missions and keeping stations and satellites in orbit, we believe electric propulsion is the best option. It produces a high specific impulse compared to the other options and the low thrust is less impactful as there is little need for quick changes in direction. The highest specific impulse is produced by Hall-Effect Electric Propulsion, which is consistently at or around 1000 - 1400 sec and Electrospray Electric Propulsion which reaches up to 3500 sec with Indium (FEEP) propellant. Xenon for the Hall-Effect Propulsion costs $120 / 100g or $1.20/g [4] while Indium (heated into a liquid once in orbit) for the Electrospray Propulsion costs ~$0.28/g [5].

Solar sails or other methods of novel/propellant-less propulsion can be used as a supplement to fuel in the case of long-term missions expected to be near a star, or for keeping a station or satellite in orbit to reduce the amount of fuel and in turn resupplies needed for continuous operation. They typically use no fuel and so are beneficial on long-term missions. If critical to the project and in use for long periods, however, the cost of potential repairs must be considered.

Chemical propulsion is not suitable for long term missions since it has a comparatively low specific impulse. It is still useful for the initial launch of the rocket or satellite however, as well as when used as a supplemental propulsion method for short, high thrust maneuvers.

6.3 Final Propulsion Recommendations

For the main propulsion system of the orbital Moon base or any future long-distance travel to planets such as Mars, we recommend Electrospray Propulsion as it has a very high specific impulse like Hall-Effect Propulsion while using cheaper fuel. A solar sail would also be a valuable supplementary propulsion system if the path of the ship passes close enough to stars.

7 Lunar Outpost Constituents

When all methods for getting to the Moon safely and reliably are undertaken and implemented, the next phase of a sustained human presence in space will be a long-term lunar outpost. This outpost, to be most effective, will have a unique construction on the surface and will include an orbital component to support the main outpost on the ground. The proposed construction and the proposed timeline of use is highlighted in this chapter.

7.1 Orbital Lunar Base

The lunar outpost will begin with the creation of an orbiting station, similar to the International Space Station, which will serve as the main support system for the outpost on the ground. There are three main reasons for this plan.

I - Maintenance of Outpost

Maintaining the ground outpost will be challenging, as (especially in the early stages of the outpost) it will be quite small, and the needs of the humans and robots in the ground outpost will not be able to be provided quickly enough in the limited space for the initial construction. Even when a fully functioning and self-sufficient lunar base is constructed on the Moon, having an orbiting base in addition will benefit the humans and robots on the Moon by providing additional space to store materials, and especially by providing a fast and easy location to send new robots down or perform major upgrades.

II – Food and Medicine

The two most crucial elements of the base for short-term and long-term success are the growing of food and the ability to have adequate medical facilities. Eventually, with a large full-scale lunar base, much of this will be able to be done on the surface, but it will always be important to have an orbiting base with easier access to shipments from Earth. The orbiting base will be the primary location for food growing and medical treatments in the early stages of construction of the surface base.

III – Transportation

Transportation is the most crucial of the three reasons for having an orbiting component of the base, as growing food, providing medical care, and maintaining the outpost on the ground will be dependent on reliably and efficiently receiving shipments from Earth. It will be easier to have an efficient, scheduled shuttle (or multiple) that utilize electrospray propulsion to quickly and efficiently move supplies and personnel rotations (which should happen frequently, as radiation will likely never be negated) from Earth to the orbiting outpost and move existing personnel and damaged or unneeded equipment back to Earth.

7.2 On-Ground Lunar Outpost

7.2a Outpost Location

The optimal area for construction of an outpost for prolonged activity will be in an area that is protected to the maximum possible extent from radiation. According to this theory, the optimal location for building a human-operated outpost will be inside Shackleton Crater, at 89.54 degrees south, 0 degrees east [11]. Shackelton Crater has been studied for years, and NASA has already targeted it as a landing site in past missions [11]. However, as well as being a good place to land a ship, it would also be a good place to build the physical surface outpost, due to its many protective properties that are mentioned below.

The most extreme form of radiation comes from outside the Moon, the horizon is the primary source of radiation [10]. This means that the outpost should have as little exposure to the unprotected horizon as possible [10]. Specifically, it is ideal that the outpost is not in constant direct sunlight. The ideal place for the outpost to be protected from as much of the horizon as possible is near a raised surface. There are many places where this could be implemented, but the optimal location, based off the possible availability of water and availability of sunlight for solar power, is Shackelton Crater [11]. An image of this crater is given below to illustrate the usefulness of this location.

Figure 16 - An image of Shackelton Crater- Johnson, D. (2022, March 3). Meet shackleton crater: Future moon landing site. Sky & Telescope. https://skyandtelescope.org/astronomy-news/meet-shackleton-crater-moon-landing-site/

Shakleton Crater is a deep impact crater on the Moon's South Pole. It offers various benefits for possible exploration, the most important of which is the darkness of most of the area occupied. The area near the right side of the image is always in darkness due to the 1.5-degree tilt of the Moon’s axis. The area near the edge to the left edge of the image is always in light, owing again to the 1.5-degree slope [11]. This unending light and darkness has three primary benefits. The first, most important benefit is that the outpost will be protected from much of the horizon. Shakleton is incredibly deep considering how wide it is [11], and this means that an outpost in this darkened area is subjected to much less of the Moon’s horizon than it would if it were on the surface. As stated above, this is one of the most effective ways to protect astronauts from radiation exposure. The other benefits of this location are a result of the unending darkness and light. The second benefit, coming from the darkness, is that, while not confirmed, there is some evidence that there is water at this location. If this is true, it is due to the low temperatures caused by the lack of sunlight to the bottom of the crater [11]. These low temperatures and lack of direct sunlight allow ice to survive while it melts in most other locations [11]. The third benefit owes to the continuous sunlight on the ridge of the crater. This sunlight gives an optimal location for solar power collection, as the sunlight never goes away. The initial outpost will be small enough so that it will not need a large number of solar panels to power it, and having continuous sunlight would allow for a small number of efficient solar panels to collect enough power to run the entire outpost. Even though not many would be needed initially, the crater is large enough that it could have a very large number of solar panels placed on it that could collect adequate energy for a large outpost [11]. Not only would this location allow for power to be collected at all times, but the lunar sky has no clouds (due to the Moon’s lack of an atmosphere), which allows these solar panels to collect more power than they would on earth, making the entire powering of the base more efficient, and significantly less unpredictable (i.e. minimal risk of blackout). This outpost location, having easy access to power, possible access to water, and protection from the horizon makes it an ideal location for an outpost to be put. Space organizations have already discussed the possibility of or begun landing in Shakleton Crater [11], but actually building an outpost in this area is optimal for a sustained human presence. As the goal of the proposed mission eventually a sustained human presence on The Moon, every effort needs to be taken to diminish the human exposure to radiation. The crater’s natural advantages and inherent radiation protection make this landing location the safest place to send humans for a long time. Further radiation protection is discussed in chapter 7.2c.

7.2b Proposed Construction and Reasons

The proposed construction of the base is a sectioned, modular compound, with separate buildings for different tasks, each of which could stand alone, which provides several logistical advantages. First, the outpost components can be easily shipped from Earth to the Moon, as each section can exist on its own. Second, it allows for easy growth of the outpost over time. The initial outpost may consist of only one or two buildings, but as the outpost grows and more humans (and robots) need to be on the surface of the Moon, it will be easy to expand the outpost. There will be no redesign necessary, and there will be no challenge of reconstructing the outpost to be larger, there will simply be a new compartment shipped from earth, which will be placed near the other components, where it can be filled easily with necessary materials, and this will create a seamless transition of size. The next main benefit of this is that this design will make damage done to the base far less serious. If the base is all one structure, if it is damaged, it will jeopardize the safety of the entire crew, and the corrective measures will be difficult and expensive. Having a modular, sectioned base will minimize damage by making it so that if one or many components are damaged, the other undamaged ones will not be in danger. Another benefit is that if damage does occur to the compartmentalized outpost, damaged components are easily replaced as they all have the same design. This will still be expensive, but another component being shipped to the Moon and replacing another will be significantly easier than reconstructing all or major parts of an entire outpost for damage done in one location. This mission proposal also suggests there be a reserve on Earth of enough compartments (enough to replace an entire outpost in case of a disaster) that can be shipped to the outpost's location if needed.

7.2c Radiation and Heat Protection in the Outpost

There is a problem of radiation on the Moon, as mentioned previously. While locating the base on Shakleton Crater will greatly help in reducing exposure to radiation, it has another benefit that has not been mentioned previously, lunar regolith [12]. Lunar regolith is abundant on the surface of the Moon and is made up of small and large particles with radiation protecting properties [12].

Lunar regolith is known to be difficult to work with. It has great variance in shape and size [12], it adheres to most surfaces and some people are even allergic to it [13]. Regolith has been the focus of many studies on radiation protection for lunar outposts. While it will likely not be sufficient on its own, it is an excellent way to begin the protection. The most promising concept is creating materials out of the regolith, which would maintain the basic structure of the regolith, maintaining its radiation shielding properties, and would make it easy to mount onto a robot or building.

Before the details of regolith utilization are examined, it will first be useful to specify the two types of radiation that are of the highest level of threat to the lunar outpost. As mentioned above, the majority of radiation on the Moon's surface comes from outside the Moon, which is why it is so important to protect the outpost from the unblocked horizon. The two main forms of radiation that need to be guarded against are Galactic Cosmic Rays and Solar Particle Events (i.e. radiation from deep space and radiation from the sun) [13]. Placing the outpost inside Shakleton Crater will help guard against much of this radiation, but as the goal of this mission is sustained human presence, to further reduce radiation, regolith-based materials will be examined to reduce radiation exposure as much as possible for humans and the robots operating at and around the outpost.

A recent study examined the effectiveness of regolith in a compound structure, also utilizing aluminum and polyethylene in protection against radiation. Specifically, polyethylene CH2 was studied, which is particularly rich in hydrogen, which is an effective safeguard against production of secondary neutrons (one factor of radiation) [13]. A simulation was conducted on a compound material using a thick layer of regolith, a thin layer of aluminum to aid in structural integrity, and polyethylene to determine the radiation mitigation effects. This study was done to determine how to make a lunar base safe for human occupation, and it was found that in order to maintain a lunar base safe for human occupation for 180 days, the regolith in the coating material would need to be present at an areal density of $160\frac{g}{cm^2}$ of the building [13]. This is doable, as there is obviously a large amount of regolith to use on the Moon. The study also measured every simulation in terms of the dosage of radiation in "blood-forming organs" [13] on the "computerized anatomical female" [13] model, which is the most appropriate model to use due to the need for sex-specific data on radiation tolerance [13]. Given that there seems to be a consensus that the regolith-coated bases would be effective in protecting human occupants, it seems likely that the same method could be used to protect robotic systems from the long-term effects of radiation.

The main issue with regards to radiation protection is economic, not scientific. It would be possible to build a very effective radiation shielding system on Earth, but this is not feasible. The cost of producing this radiation protection on Earth (which is already expensive) and then shipping it to space would not be economically viable. The shipping costs to space are too high for this to be sustained [14]. Even if humans are successful at bringing down space shipping costs, it will always be cheaper to create the resources needed with what is already at the landing site, and this will always make repairs easier as well (especially in later stages of the outpost if these materials can be mass-produced on site). Therefore, creating radiation shielding materials from those already available will be important for a continued presence in space.

The technical results of the experiments were that the effective dose of radiation decreased very quickly while areal density increased, and this trend was especially severe for the February 1956 SPE event [13]. The graphs are shown below. This use of regolith coating should be advanced to include robotic systems, but this is of primary importance in protecting the surface outpost. The following images demonstrate the efficacy of this proposed material in radiation shielding for both Solar Particle Events (SPE) and Galactic Cosmic Rays (GCR) [13].

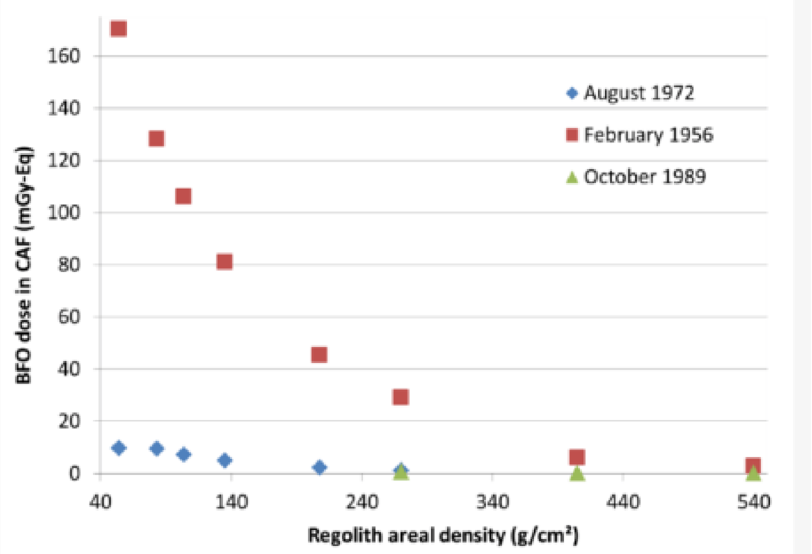
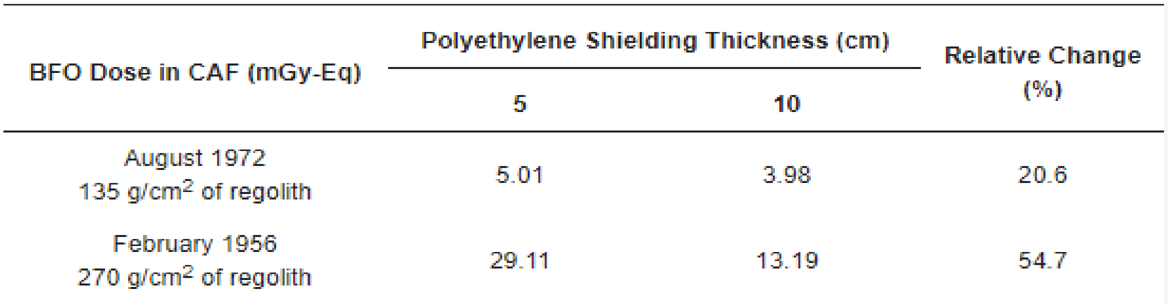


Figure 17 - Radiation dose from different Solar Particle Events from three different months - Akisheva, Yulia, and Yves Gourinat. 2021. "Utilization of Moon Regolith for Radiation Protection and Thermal Insulation in Permanent Lunar Habitats" Applied Sciences 11, no. 9: 3853. https://doi.org/10.3390/app11093853

In the above image [13], The proposed material for radiation protection was simulated against three major historical Solar Particle Events in August 1972, February 1956, and October 1989 [13]. The results were that lower regolith areal density correlated with a higher dose of radiation. This was especially true in the case of the February 1956 event. The 1989 event had the lowest change in radiation, but the worst scenarios must always be treated as the most likely. The highest areal density in the simulation of the three solar particle events was $2.7\ \frac{g}{cm^2}$[13]. Understanding that the worst case must be prepared for, this mission proposal recommends that the minimum density of the regolith used be $2.7\ \frac{g}{cm^2}$. A numeric comparison of the thickness of the polyethylene shield and the radiation dose for the 1956 and 1972 events is provided below.



BFO Dose in CAF (mGy-Eq)	Polyethylene Shielding Thickness (cm)		Relative Change (%)
	5	10	
August 1972 135 g/cm^2 of regolith	5.01	3.98	20.6
February 1956 270 g/cm^2 of regolith	29.11	13.19	54.7

Figure 18 - Radiation dose from different polyethylene shielding thickness - Akisheva, Yulia, and Yves Gourinat. 2021. "Utilization of Moon Regolith for Radiation Protection and Thermal Insulation in Permanent Lunar Habitats" Applied Sciences 11, no. 9: 3853. https://doi.org/10.3390/app11093853

Demonstrated in this table, the increase in the thickness of the polyethylene part of the material from 5 cm to 10 cm correlated with a significant reduction in the radiation dose of the two stronger solar particle events (1956 and 1972). Also mentioned in the study, this effect worked in conjunction with the thickening of the regolith areal density, meaning that thickening the polyethylene shielding within the material decreases the radiation dose beyond the minimum level achieved by making the regolith denser [13]. Again, in preparation for the worst-case scenario, this mission proposal recommends that the polyethylene shield be at least 10 cm thick.

Also important for radiation protection is protection from galactic cosmic rays (GCR’s). GCR waves come from outside our solar system and are extremely powerful [13]. These waves experience changes in intensity over time, and making protection from them even more important, the cycle extending into 2031 is expected to have increasing strength [13]. The surface lunar outpost is protected from a fair amount of radiation from the Sun by its position in the shadows at the bottom, but it has less natural protection from GCR waves. There is still better protection than there would be from a base on the surface not protected by walls of a crater, but the base will still have enough exposure to the horizon to warrant additional protection from

GCR's. The following diagram shows the protection level for increasing density of regolith in a compound material with polyethylene and aluminum (to aid in structural rigidity) [13].

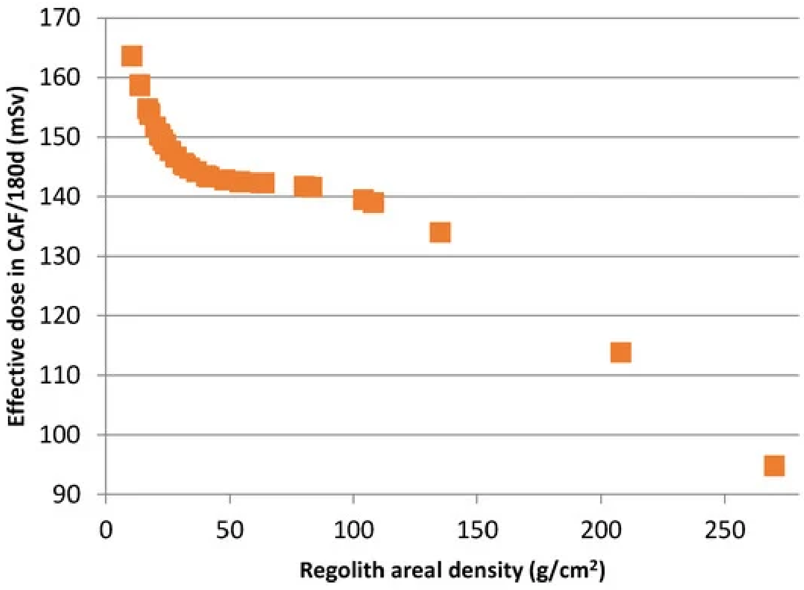
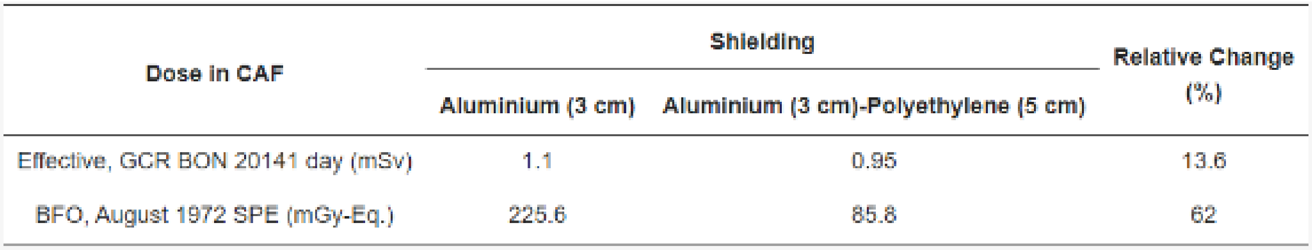


Figure 19 - Radiation dose recieved with different areal densities of regolith - Akisheva, Yulia, and Yves Gourinat. 2021. "Utilization of Moon Regolith for Radiation Protection and Thermal Insulation in Permanent Lunar Habitats" Applied Sciences 11, no. 9: 3853. https://doi.org/10.3390/app11093853

As seen in the diagram, the increase in regolith density is correlated with an increase in radiation dose protection, just as was seen with protection from SPE waves. The protection increase is minimal for small increases, especially in the middle, but very large for large increases, with the radiation dose reducing from above 160 mSv to below 100 mSv when regolith areal density passes 250 $\frac{g}{cm^2}$ [13]. Again, assuming that the predictions for increased upcoming GCR activity are correct, the material used for radiation shielding should have regolith areal density of at least 250 $\frac{g}{cm^2}$.

Another important aspect of this experiment was its simulation of materials used to protect lunar rovers. The mission proposal of this report is to have minimal human activity outside the better-protected outpost. However, this experiment is important because it directly shows the effect of a polyethylene layer for radiation protection. The results of the simulation of radiation protection behind aluminum compared with protection behind aluminum and polyethylene are shown in the table below.

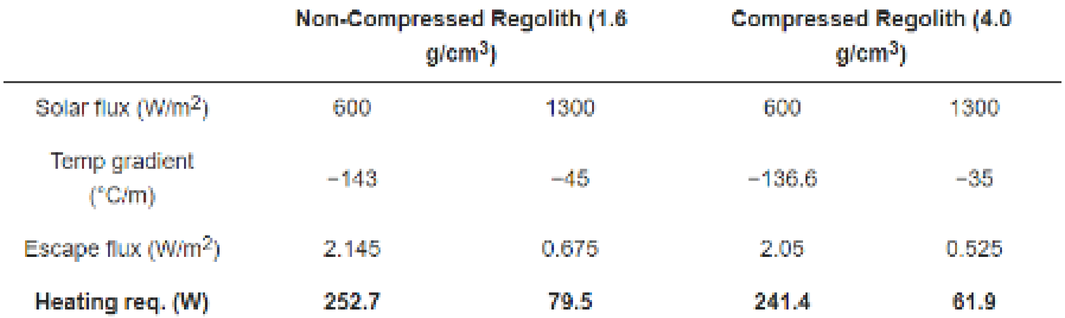


Dose in CAF	Shielding		Relative Change (%)
	Aluminium (3 cm)	Aluminium (3 cm)-Polyethylene (5 cm)	
Effective, GCR BON 20141 day (mSv)	1.1	0.95	13.6
BFO, August 1972 SPE (mGy-Eq.)	225.6	85.8	62

Figure 20 - Radiation dose from shielded and unshielded aluminum - Akisheva, Yulia, and Yves Gourinat. 2021. "Utilisation of Moon Regolith for Radiation Protection and Thermal Insulation in Permanent Lunar Habitats" Applied Sciences 11, no. 9: 3853. https://doi.org/10.3390/app11093853

As seen in the table above, the addition of 5 cm of polyethylene to the existing 3 cm of aluminum has a significant effect on the radiation dose. While useful (a 13.6 percent reduction) for galactic cosmic rays, this addition had an even more pronounced effect on the radiation dosage from the August 1972 SPE (a 62 percent reduction) [14]. This result is integral to the experiment, as significant protection is still gained by having a protective layer of polyethylene. This further reinforces this report’s recommendation that polyethylene must be used in the regolith-based materials to increase radiation protection, especially from SPE’s. If this polyethylene shielding is used in conjunction with the regolith that was experimented with, the radiation protection of the base would increase, because as previously stated the radiation protection of different materials is compounded when they are used together [13].

Another important aspect of the lunar outpost is heating. The Moon can have temperatures of under -180°C, clearly making heating the base an important goal. Efficiency is always an important aspect of a space exploration mission, but in the early stages of a lunar outpost on the surface, it becomes even more critical, as resources need to be used sparingly in case of a disaster that the outpost does not yet have the resources to quickly deal with. In the long term, efficiency is important too, because it allows more money and resources to be devoted to exploring space, not just maintaining the outpost. To make the outpost safe while using as little energy as possible, heat retention needs to be maximized. Along with its ability to protect against radiation, lunar regolith is also very effective at retaining heat, meaning far less power is needed to heat the outpost that is coated with the regolith compound material proposed than it is to heat an outpost without a layer of regolith protecting it [14]. The table below shows the results of an experiment in heat retention using a 5-meter wide and 5-meter tall cylinder that is coated with regolith, with one experiment conducted with uncompressed regolith ($4.0\frac{g}{cm^3}$) and another with uncompressed regolith (1.6$\frac{g}{cm^3}$). The goal of the experiment was to maintain an internal temperature of 20°C [14].



	Non-Compressed Regolith (1.6 g/cm^3)		Compressed Regolith (4.0 g/cm^3)	
Solar flux (W/m^2)	600	1300	600	1300
Temp gradient (°C/m)	−143	−45	−136.6	−35
Escape flux (W/m^2)	2.145	0.675	2.05	0.525
Heating req. (W)	**252.7**	**79.5**	**241.4**	**61.9**

Figure 21 - Differences in energy needed to heat a structure protected by compressed and non-compressed regolith - Akisheva, Yulia, and Yves Gourinat. 2021. "Utilization of Moon Regolith for Radiation Protection and Thermal Insulation in Permanent Lunar Habitats" Applied Sciences 11, no. 9: 3853. https://doi.org/10.3390/app11093853

Seen in the table, the energy required to keep the base at a safe internal temperature is low, and this is due to the fact that regolith is an excellent insulator [14]. Another important result that this experiment reached is that it is important for the regolith to be compressed, as the compresses regolith insulates better than the non-compressed regolith, although non-compressed regolith still provides benefit [14].

Given the promising results of the use of regolith-based materials to protect the outpost from radiation and maintain safe internal temperatures efficiently, the proposed outpost will be constructed with a protective layer of regolith-polyethylene-aluminum compound material. The regolith should be compressed to 4.0 $\frac{g}{cm^3}$, with areal density of at least 250 $\frac{g}{cm^2}$, along with a 5 cm to 10 cm layer of polyethene, and 3 mm of aluminum for structural integrity.

7.2d Radiation Protection for Robots

One of the major challenges to robotic exploration on the surface of the Moon is radiation. Radiation can cause a variety of problems to electronics. The first issue that can arise is a bit-flipping effect, where one or a small number of bits of information are corrupted. While this is not a long-term effect, it can lead to computer errors, and an exploration robot would need to store data that should not be corrupted. The second effect of radiation on electronics is more serious and is called a “total ionizing dose effect” [16]. This effect is long term, and it slowly breaks down the electronics, damaging transistors and causing circuits to leak [16]. The solution to this problem is radiation-hardened electronics [16]. There are multiple ways to achieve radiation hardening. The first method is to either create the device out of or protect parts of the device with a radiation absorbing material, such as lead or tungsten. Another method is to create components that are naturally less susceptible to radiation. One way of doing this is to embed the electronics in materials that can deter the effects of radiation, and another way is to strategically position radiation susceptible parts so that they have minimal exposure [16].

While there are many ways to create radiation-hardened electronics, there are some problems, mainly, they are very expensive, and they typically have slower performance than non-radiation-hardened electronics [17]. The optimal solution is a combination of radiation hardening and having a lunar outpost made of the regolith-polyethylene-aluminum material to guard against radiation. Then, this allows the focus to switch to the immediate effects of radiation such as bit flipping. If the robots re-enter the outpost frequently enough, even if bit flipping did occur, there would be enough time to save necessary information with minimal loss. While radiation will eventually have cumulative effects, giving the robots a place where they can go to receive regular maintenance and now have the radiation continuously affecting them will make them serviceable at their jobs for much longer than they will be if they are sent up alone, made of heavy expansive materials, and left without any repair options.

Added to the prospect of allowing the robots to pass into and out of a maintenance facility, the regolith-polyethylene-aluminum material that will be used to protect the buildings making up the outpost should be used on robots where possible. This material, as discussed in 7.2c, is incredibly effective at blocking radiation. This will be of primary importance for larger robots that need to move around the Moon for a long time. In the case of smaller, less expensive robots, other factors such as repair or replacement are more viable than for larger robots, making this still an important possibility, but not as important as it will be for large, expensive robots. Therefore, this mission proposal recommends that the larger robots that are more difficult to repair and replace take precedence for being protected by the compound material.

For the smaller robots operating on the Moon, as well as the ones that can return to the outpost very frequently, alternative methods for radiation protection can be used in place of, or, ideally, in conjunction with the inclusion of the compound material. For these robots that do not need to protect as strongly against the radiation from the horizon in its many forms are primarily threatened by the regolith on the surfaces they will explore. The regolith dust presents the most significant challenge, as along with its negative electric charge, it is very adhesive, which can destroy electronics. Of the ways to handle this problem, there are two very promising ideas, cleaning the robot itself, or complete removal or prevention of lunar dust.

Within the removal category, there are two methods. The first is to have the robot hover above the surface of the Moon, and the second is to remove lunar dust from the surface entirely, which would be a very difficult project, but likely workable in isolated circumstances. For the hovering solution, MIT researchers tested a rover that utilizes the charge of the lunar dust to hover above the surface of the Moon, which would allow the robot to be free of contamination and protect the electronics of the device [18]. In the initial study, a two-pound device was able to hover over the simulated Moon's surface (tested in a laboratory). This is easier to do on smaller asteroids, but the Moon's large size leads to a greater gravitational pull that makes it harder [18]. The method used ion thrusters to attempt to levitate, which are negatively charged, resulting in the device gaining a positive charge from shooting negative ions away from itself. Along with doing this, the device also projected positively charged ions at the surface, increasing its positive charge [18]. More testing is needed, but the result was promising. The following image demonstrates how the experiment was done, by adding an ion thruster to a test vehicle above an aluminum plate, with the vehicle supported by springs to account for Earth's gravity, and with a tungsten rod to measure the force produced [18].

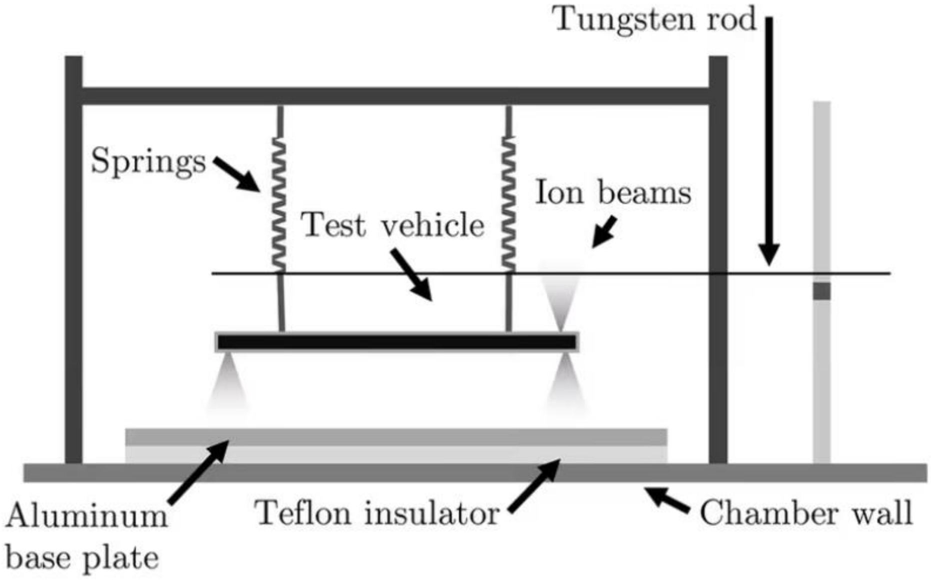


Figure 22 - The technical setup of the experiment for a hovering robot - Coxworth, B. (2021, December 23). MIT-designed "Flying saucer" may one day hover its way across the Moon. New Atlas. https://newatlas.com/space/mit-levitating-flying-saucer-moon/

The result of this experiment was the conclusion that a 2-pound robot would be able to move about 1 cm off the surface of the Moon with a small amount of power, and increasing the power will make larger robots able to hover [18]. While promising, this report recommends using the hovering solution, at least in early stages, as a method only for very small and light robots. A swarm of robots exploring a large area for a brief period would be a good way to use these types of robots.

Another method for lunar exploration would be to remove the dust from the robot before it could eat away at the electronics. A research team at the University of Colorado at Boulder tested a method that would use an electron beam to remove lunar dust while leaving the surface that it was on unharmed [19]. This idea is particularly interesting as it could be done for robots of all sizes and could even extend beyond robots. This electron beam would negatively charge the surface that was covered in lunar regolith, leading to a repelling of lunar dust. This method was tested using “lunar stimulant,” which is designed by NASA to closely mimic lunar regolith [19]. When tested in a vacuum, between 75 and 85 percent of the stimulant was removed using this lunar beam [19]. With the development of increasingly powerful electron beams, this cleaning mechanism will become easier to implement effectively. Even at the current stage of development, it will be a very helpful part of the removal of regolith from robots.

This leads to some possible ideas for improving robotic exploration on the Moon. If this electron beam can be improved, a robot exploring the surface of the Moon could be returned to a mobile cleaning station where the regolith could be removed. Even if all the regolith is not cleaned off, removing some of it could lengthen the robot's survival. When examining the hovering robot possibility, swarm robotics could be utilized. If the robots could all hover and communicate with each other and back to a central lunar exploration base, this would eliminate the need to have a small number of robots actually on the surface and in constant need of cleaning. At the same time, this would increase the area of the lunar surface that could be explored, as many of the smaller robots could be spread over a larger area. The base could be used for recharging the robots (or replacing batteries), and each device would need less power on account of their size. The logistical challenge presented in this circumstance would be getting sufficient power. Even though each individual robot will require less power, when added together, the power requirement will be high. To combat this, a staggered release could be used, sending out the robots over an extended period of time to allow for a regaining of power at the base where recharging takes place before more need to be charged.

A third, and significantly more challenging idea is a lunar excavation. Regolith is generally between 5 and 10 meters deep, so removing it over a large area would be difficult. However, if there is a specific area of the Moon that scientists want to explore, a small-scale excavation could take place, and allow for a larger robot to explore and gather data. NASA is working on a project for lunar excavation for resources, and a similar technology could possibly be used to clear sections of Moon dust [20]. This is a new initiative and is currently being run as a competition [20]. This idea will be challenging for large scale lunar exploration but has promise for a concentrated exploration effort. The lunar excavation would remove lunar dust from the area of exploration, narrowing the area to be excavated down significantly, allowing the project to be completed in less time [20]. This will, however, result in the same challenges as exploration without prior excavation, because the excavating crafts will be under the same duress as the other robots on the Moon. These machines would need to be regularly maintained to be effective, as it would not be economically viable to constantly need to create new ones. Therefore, this idea only makes sense, in terms of surface exploration, if there is a specific, small area that needs to be excavated in order to be adequately explored. Of course, if drilling is ever necessary (which it likely will be in order to mine for materials and search for water underground), this idea is both promising and the most practical.

For both the protection of robots from the harm of radiation and the removal of lunar regolith, this report recommends that there be a combination of strategies used. First, large robots that will travel for long periods of time and will be exposed to substantial radiation should be protected by the compound regolith-polyethylene-aluminum material, and radiation hardened to every extent possible. Second, robots that rely most on maneuverability should hover above the surface in swarms, emphasizing fast missions that minimize radiation exposure and get back to a protected place as fast as possible. Third, if there is a small area of the mission that will require extensive search on the surface, or if there is an underground area that needs to be drilled into, a small-scale excavation can take place, but this should be avoided for large-scale missions wherever possible for time and economic reasons. Where this excavation could be needed is mission-specific, but in the case of mining for resources, this excavation should be considered by the mission controllers.

7.2e Protection for Humans

The best protective measure for humans in space is to limit time spent on the surface, and when they must be on the surface, time spent outside the base should be limited to every possible extent. The only safe level of radiation is none, and while this is likely impossible to achieve, preventative measures can be taken. While astronaut suits are already designed to protect against radiation, every effort needs to be taken to prevent exposure in the first place. The details outlined in chapters 7.2a, 7.2b, 7.2c, and 7.2d create a framework for limitation of human exposure to the hostile environment. Crewed exploration missions, with set return dates, are not likely to be discouraged by radiation [15]. Radiation will always be a consideration, and preventative measures must always be taken, but the true threat of radiation comes into play when trying to attain a sustained human presence on the Moon. For a sustained human presence, the majority of exploration and off-outpost activities must be left to robots, with humans primarily remaining at the surface outpost or located in the orbiting station. The humans on the surface will primarily work as technicians for the robots, researchers gathering data and conducting tests with materials retrieved by robots, and maintainers of the base (in conjunction with robots). The rest of the humans will be located in the orbital base, which will be protected from radiation the same way as the surface outpost, with the compound regolith-polyethylene-aluminum material. This does permanently decrease the need for humans in space exploration, but they will still retain the important role of mission controllers, and a general decrease in human necessity is unavoidable as humans create machines capable of doing things that they are not.

7.2f Personnel and Supply Options

Personnel Rotation

In the early stages of the lunar outpost, there will be more humans than is the end goal, and construction of the outpost will be a phase where there is not adequate radiation protection. The modular design of the base should minimize this period of poor protection greatly, making the main concern the amount of people who are exposed, which will require larger and more frequent rotations to address. Generally, astronauts stay in space for about six months, although there is variation [21]. These are good starting guidelines while humans work to make the base operational. While the orbital component is similar in structure and purpose to the International

Space Station (ISS), it is important to note that the ISS is protected by Earth's atmosphere [22]. As a result, the lunar base's orbital component must have frequent personnel rotations and a robust radiation protection mechanism (proposed in above sections). As the outpost grows, and the development stages continue to cycle, the radiation protection mechanisms will become better and more effective. There will be adequate time to cover all necessary structures with the compound material, and while this is being done there will be time for more research and experiments that will lead to better radiation protecting mechanisms being developed and implemented. As this happens, the need for personnel rotations will still exist, but it will be able to happen less frequently, as humans will be leaving the surface outpost only in increasingly large time intervals as the robotic presence increases with more time and money dedicated to the lunar program from Earth, and there will only be a small number of humans on the surface due to the robots being able to handle most of what needs to be done on the surface. The goal, as previously stated, is to get the lunar outpost and orbital base to a point where humans control the missions and direct experiments, but most of the manual work and the exploration in dangerous, unprotected conditions is done by robots.

Food and Water

In the early stages of the lunar outpost and orbital station, food and water will need to be brought from Earth. Shipping costs to space are incredibly high [14], and logistically this is not ideal. However, there are two things that will be utilized to make human existence possible without constant shipments of food and water from Earth. First, hydroponics will be used to grow food. This should be done on the orbital component of the outpost wherever possible to keep the surface outpost as small as possible, and because the majority of the humans will always be on the orbital component of the base. It will be easier to grow food for a large number of and people on the orbital component and send a small amount down for a small number of people than it will be to grow the food on the surface of the Moon. The next thing that will be helpful is the likely availability of water inside Shackelton Crater. If robots are used to harvest this ice and send it back to the station to be melted and used for drinking, the problem of water will be solved. This is a very attainable solution, with the robots that would harvest the ice in the crater needing less radiation protection to begin with (less exposure to SPE's and GCR's), making it a cost-effective mission, and it will not be a long journey from the ice location to the base location where it can be launched to the orbital component.

Medical & Maintenance

As long as there are humans, present on either the surface or the orbital component, there will need to be a doctor that is easily accessible. Similarly, there will need to be a technician to repair damaged robots. As technology advances further, the doctor will be aided more and more by robots and AI, so there will likely never need to be a full medical team. Similarly, the robot technician will be aided greatly by robots that can repair themselves and others, and this ability will only increase with time. As the robotic presence grows, there will likely still only need to be one technician to oversee the entire procedure of deployment of robotic systems.

7.3 Role of Robots

7.3a Exploration

As mentioned above, the ultimate goal of advances in robotic technology is to have robots be more effective than humans at exploration, allowing humans to be able to control missions while robots undertake dangerous missions. For broad-scale lunar exploration on the surface, the approach mentioned in the above section on hovering robots is promising, especially with the use of swarm robotics. However, for exploration of lunar caves, which are currently sought-after places to map and explore, a different system will need to be used. This example will also well-illustrate a case where a large, expensive robot will be used and need to be protected well from radiation due to prolonged trips outside the outpost.

Lava tubes have a unique set of challenges in exploration. They do have protection from radiation, but they lack the lighting of the surface [23]. Along with being protected from most radiation, they are also protected from meteorites [24]. These factors allow for a smaller, less structurally sound, and cheaper robot to explore these locations, with the only problem being supplying it with power. A research team at The University of Oviedo developed a proposed method of lava tube exploration for the European Space Agency. This proposed method has a large robot stationed outside the entrance to the lava tube, from which is lowered down a “Charging head” [23], which supplies power to the robots that are exploring inside the cave through wireless power. Some of the robots in the cave would be able to act as intermediaries, transmitting power from the wireless charging station lowered down the tube to the robots that are further along in the tube [23].

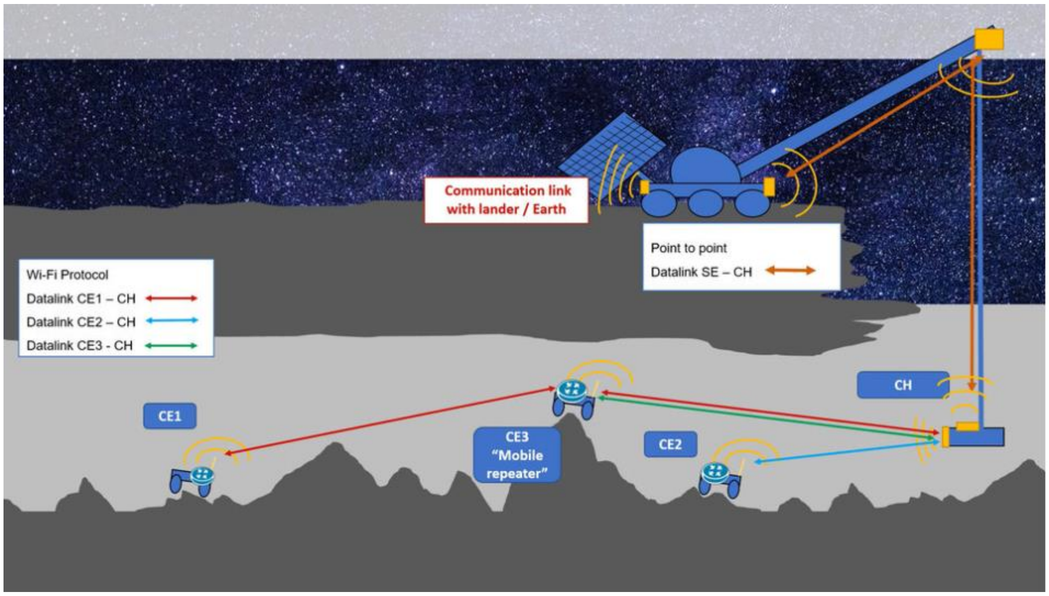


Figure 23 - Proposal from The University of Oviedo for lunar cave exploration missions - ESA. (2021, February 24). ESA plans mission to explore Lunar Caves. ESA. https://www.esa.int/Enabling_Support/Preparing_for_the_Future/Discovery_and_Preparation/ESA_plans_mission_to_explore_lunar_caves

The above image demonstrates the details of The University of Oviedo’s proposal. The specific proposal that was developed for the European Space Agency states that the large robot stationed at the entrance to the lava tube should be in communication with either Earth or a lander [23], and this can easily be changed to being in communication with a permanent lunar outpost. Since there will be a permanent lunar outpost, there are two main options for exploration of lava tubes.

The first method that can be used is releasing the large robot at the entrance from the orbital component of the outpost. With this method, the larger robot will be released from the orbital base, and land near the lava tube. The smaller robots, as an extension of the proposal in the above paragraph, will be housed inside the larger robot, and released upon landing. From here, the mission can proceed as above, and the lava tube can be explored.

The second method considered is having the larger robot, still housing the smaller robots, travel to the desired lava tube from the surface outpost. This could take longer, as the larger robot would travel relatively slower than the orbital outpost, but multiple robots could disembark for different missions at once, which would likely make up for the speed lost by having the robots need to travel the whole distance to the lava tubes.

These ideas can be extended beyond just lava tube exploration and can include exploration of the surface in general. Robots that will be exploring Shackelton Crater and the surrounding areas can depart from the surface outpost (which may later be extended to other craters or even into lava tubes themselves, extending the radius for surface outpost departure). However, robots that have an especially long journey to get to the exploration site will be aided by the orbital outpost, which can shorten the journey if it does not get the robot to the exact location.

7.3b On-site maintenance

Another important aspect of a robotic presence on the Moon is outpost maintenance. In order to keep the outpost properly maintained, especially as it grows larger and more complex in its later stages of development, robots will need to do work on and around the outpost as well. There are two main sections of the base that will need frequent maintenance. First, and most importantly, the outpost will have solar panels set up in the section of Shackelton Crater that is in perpetual light. These solar panels will be protected from radiation through radiation hardening, but repair will still need to be made due to the extreme nature of lunar radiation, as well as the naturally harsh environment on the Moon. Robots will need to travel to these solar panels and replace and repair them. The second area where robots will be needed is in the maintenance of the other robots. Robots will wear down over time due to radiation and the Moon's hostile environment. In the later stages of the outpost, there will not be enough humans on the base to maintain all the robots necessary. Instead, there will be one technician who will serve as a manager for a team of robots that specialize in maintaining the exploration fleet.

8 Humans and Space

8.1 Gene Editing

For humans to have a long-term, sustained presence in space, gene editing will need to take place. This will allow humans to be well adapted to life in space, where they will be able to stay longer before being replaced by new personnel. If gene editing technology advances to a very possible point in the coming years, it may even be possible to have humans live in space in perpetuity. Inspiration will be drawn from the animal kingdom, and human DNA will be edited to match that of radiation resistant animals such as the Tardigrade, experimentation has already begun on this [26]. This method of editing human genes is incredibly contentious, and great care needs to be taken to ensure that this is done properly. It is expected that it is far off for this technology to take effect, but it is not unreasonable to assume that it could happen very fast if humans need to compete with Artificial intelligence.

8.2 Artificial Intelligence

Artificial intelligence is increasing at a rapid pace, and it will lead to competition with humans in every field. In almost all cases, machines and AI are cheaper, more effective, and less prone to need replacement than humans are. This progress in technology will not slow down and will eventually lead to human obsoletion in most cases. However, as this point has not yet been reached, there will be a power struggle between humans and machines, which will be the primary driver for gene editing at an earlier stage than is currently expected. As machines become mass-produced, smarter, and more effective, humans will need to find ways to compete with them. The human brain can likely never become as advanced as Artificial General Intelligence will become, and humans cannot be ethically mass-produced, which leaves the only way they can continue to be competitive as physical effectiveness. Clearly, this will not work in perpetuity, but while mechanical technology is still being worked on, humans will attempt to make themselves as useful as possible while they still have this advantage. While robots are still susceptible to radiation, humans could be edited to be insusceptible, which would reduce the economic cost of sending humans to space to below the cost of sending expensive robots with radiation protection to space. Similarly, if humans are edited to be less susceptible to low gravity, then they will be able to be in space almost in perpetuity. This will allow a human presence to not need to be interrupted by crew changes, which will provide another benefit to humans over robots. However, as robotic technology advances even further, and radiation protection becomes more effective and cheaper, the role of humans will be forcibly diminished to simply controlling the missions, and even here they will be aided by artificial intelligence.

8.3 Phasing Out Humans

Even though the role of humanity will diminish, it will not be unimportant. Humans, barring a possible loss of control of Artificial Intelligence, will still be the controllers of artificial intelligence. Robots equipped with artificial intelligence are eventually going to be better suited to space exploration than even genetically modified humans. They are not susceptible to injury in the way that humans are, they can travel further than humans can without the need for sustenance, and they are not susceptible to the psychological trouble faced by humans in long periods of isolation. As such, it makes sense that humans, after realizing that they cannot compete with robots in terms of effectiveness, will become mission controllers. Details of missions will be aided by artificial intelligence, but the reasons for going on missions, the primary objectives for the missions, and the decision to go on the missions will be made by the humans controlling the robots and creating the artificial intelligence. Of course, There is always the risk of humans losing control of the artificial intelligence and robots, which would be a disaster, as they will be more powerful than any human. However, if appropriate safeguards are put in place, this will be largely avoidable, making humans largely obsolete, but not extinct. If humans still exist, and they have control of the robots, they will have an important role to play in space exploration, as the robots would likely not decide to explore space unless directed (again, this is reliant on the structure of the artificial intelligence they are given, which can only be speculated on at this point in time). Humans will still direct robots and artificial intelligence to explore space, even if there is not much work for humanity to do.

9 Conclusion

Once the Moon is safely and consistently reached, a two-component outpost will be built. The first component will be orbital. Similar to the International Space Station orbiting Earth, the orbital component of the lunar outpost will orbit the Moon and will have a crew on board to both support the crew on the surface of the Moon (such as hydroponically growing food) and to conduct additional work on the orbital component itself. There will also be a surface component of the outpost, which will be located in Shackelton Crater, a crater at the Moon’s South Pole with most of its interior protected from dangerous forms of radiation due to the constant darkness inside [11]. Another benefit of the Shackelton Crater location is the likelihood of ice at the bottom, preserved by darkness and cold temperatures [11]. Also, the rim of Shackelton Crater is always in sunlight, making it an optimal location for the placement of solar panels [11]. Both the orbital component and the surface component will utilize a specialized material made from a compounding of condensed regolith with a polyethylene shield, supported by aluminum. For the orbital base, this will shield against radiation, and for the surface base, not only will it shield against radiation, but it will be of great use in insulating the outpost, which will be in a very cold location [13].

This compound material will also be used in the construction of large robots that undertake missions to protect them from the harmful effects of radiation. Electron beams will be used to clean the harmful lunar regolith off the robots when they return to the outpost, and robots that are small and light enough will hover above the lunar surface to avoid most of the contamination with regolith. For exploration of the Moon, there will be two components. First, there will be robots that explore the surface, which will be done by driving around the Moon in the case of a wheeled robot, or hovering above the surface in the case of a swarm robotics mission where a large amount of space needs to be explored. Second, there will be dedicated cave and lava tube exploring robots. These robots will work together to move and process information. There will be a large robot that sits at the entrance to the cave or lava tube, and this robot will house the smaller robots. The swarm will then enter the cave or lava tube and will be charged wirelessly from an appendage lowered down from the larger robot. The swarm will act as repeaters to each other, sending the wireless charge further down the cave or lava tube to robots that could not be charged from the place that the appendage is lowered down into. For transportation of the robots to the exploration location, both for surface and underground exploration, robots will be dispatched from the outpost and will move to the necessary location. In the case of especially long journeys, a small number of functioning robots may be kept on the orbital component of the base so that they can be quickly moved near to where they need to gather data.

For the propulsion system of the orbital Moon base, we recommend Electrospray Propulsion because of its very high specific impulse. Supplementary propulsion like a solar sail would also be viable to save on fuel. Chemical propulsion is not a viable option for the long-term operation of a base and should only be used in situations where high thrust is needed such as the initial launch from Earth’s surface. Electrospray Propulsion or Hall-Effect should also be employed on any future long-distance missions to planets such as Mars.

Personnel on the outpost will be minimal on the surface, as ideally only a few people will be needed to maintain it when assisted by robots. Most people will be located on the orbital component, but this number should also decrease with advances in robotics continuing to be made. As long as there are any people on the outpost, either on the surface or in orbit, there will be at least one doctor, who, especially in coming years, will be greatly assisted by robots. Also, there will only need to be one robotic technician, as this person will be able to receive a large amount of help from robotic counterparts as they repair and rebuild robotic systems. The rest of the personnel will be directing the missions and ensuring that operations at the outpost remain steady, but the need for them to leave the base will be minimal, and ideally this will, in the very near future, become not at all.

Artificial Intelligence is improving at a rapid pace, and it will soon become intricately involved with every aspect of not only space exploration, but life in general. The unavoidable consequence of this is that the need for humans in space exploration will decrease greatly. Gene editing will take place, and experiments inserting Tardigrade DNA into human cells have already begun [26]. This will make it safer for humans to exist on bases in space, but as advances in robotic technology and Artificial Intelligence become greater and occur more frequently, there will be no reason for humans to ever even leave bases. This leaves Humanity with a very diminished role in space exploration, but still an important one, the job of mission controllers. Humans will remain in charge of the robots (at least for the foreseeable future), but their only job in space exploration will be to control the mission and set goals. This does not decrease the benefit of space exploration to Humanity, as the benefits of exploring and extending Human knowledge throughout space will satisfy not only satisfy curiosity but will address some of the most pressing challenges the species faces.

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12 Appendix A: MATLAB

Orbital Simulation

```
clc; clear; close all;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% INPUT AND CONSTANT PARAMETERS

gravParamEarth= 398601.88; % Earth's gravitational parameter
gravParamMoon= 4903.84; % Moon's gravitational parameter

% Moon orbital parameters:
eccentricityMoon= 0.0549; % eccentricity
semimajorAxisMoon= 384400; % semimajor axis [km]
periodMoon= 2 * pi * sqrt(semimajorAxisMoon^3 / gravParamEarth); % full period of
motion [s]

% Flyby orbital parameters rel. moon
eccentricityFlyby= 0; % eccentricity
semimajorAxisFlyby= 6000; % semimajor axis [km]
periodFlyby= 2 * pi * sqrt(semimajorAxisFlyby^3 / gravParamMoon); % full period of
motion [s]

% Hohmann orbital parameters:
eccentricityHohmann= 0.9554; % eccentricity
semimajorAxisHohmann= (semimajorAxisFlyby + 9378 + 405500)/2; % semimajor axis [km]
periodHohmann= 2 * pi * sqrt(semimajorAxisHohmann^3 / gravParamEarth); % full period
of motion [s]

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% ORBITAL FUNCTIONS

% Moon's radius [km] as function of true anomaly [rad]:
r_M= @(phi) (semimajorAxisMoon * (1 - eccentricityMoon^2))./(1 + eccentricityMoon *
cos(phi));

% Spacecraft's radius [km] as function of true anomaly [rad] during Hohmann transfer:
r_H= @(phi) (semimajorAxisHohmann * (1 - eccentricityHohmann^2))./(1 +
eccentricityHohmann * cos(phi));

% Spacecraft's radius [km] as function of true anomaly [rad] during flyby:
r_fb= @(phi) (semimajorAxisFlyby * (1 - eccentricityFlyby^2))./(1 + eccentricityFlyby
* cos(phi));

theta= 0:pi/100:2*pi;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% CREATING LOCATION TABLES RESPECTIVE OF TIME

% Initializing
j= 0; locationTableMoon= [];
i= 0; locationTableSpacecraft= [];
plotCraft= 0;

TransferStartTime= 715281; % Beginning of the Hohmann transfer
```

```
returnTime= periodMoon/2 + 3*periodFlyby;

for t= 194*3600 : 1800 : periodMoon

    % First we find the position of the Moon in its orbit at time t:
    meanAnomalyMoon= 2 * pi * t/periodMoon; % mean anomaly [rad] at t
    % find root
    fM= @(eccentricAnomalyMoon) eccentricAnomalyMoon - eccentricityMoon *
    sin(eccentricAnomalyMoon) - meanAnomalyMoon;
    solM= fzero(fM, 0);

    % Now we calculate the ture anomaly of the moon from the eccentric anomaly:
    trueAnomalyMoon= 2*atan(sqrt((1 + eccentricityMoon)/(1 - eccentricityMoon)) *
    tan(solM/2)); % the true anomaly [rad] from solM


    i= i+1; % Update chart increment

    % Save location of the Moon and spacecraft in table:
    locationTableMoon(i,1)= t/3600;
    locationTableMoon(i,2)= trueAnomalyMoon;
    locationTableMoon(i,3)= r_M(trueAnomalyMoon);

    locationTableSpacecraft(i,1)= t/3600;
    locationTableSpacecraft(i,2)= 0;
    locationTableSpacecraft(i,3)= 0;


    if t >= TransferStartTime && t <= periodMoon/2 % duration of the Hohmann transfer

        % Now we find the location of the spacecraft in the Hohmann transfer orbit at
        time t:
        meanAnomalyHohmann= 2 * pi * (t - TransferStartTime)/periodHohmann; % mean
        anomaly [rad] at t
        % Find root
        fH= @(eccentricAnomalyHohmann) eccentricAnomalyHohmann - eccentricityHohmann
        * sin(eccentricAnomalyHohmann) - meanAnomalyHohmann;
        solH= fzero(fH, 0);

        % Now we calculate the ture anomaly of the spacecraft from the eccentric
        anomaly:
        trueAnomalyHohmann= 2 * atan(sqrt((1 + eccentricityHohmann) / (1 -
        eccentricityHohmann)) * tan(solH/2)); % the true anomaly [rad] from solH

        % Save location of the spacecraft in table:
        locationTableSpacecraft(i,1)= t/3600;
        locationTableSpacecraft(i,2)= trueAnomalyHohmann;
        locationTableSpacecraft(i,3)= r_H(trueAnomalyHohmann);

    else
        if t >= periodMoon/2 && t < returnTime % duration of the lunar-centric flyby

            % Now we find the location of the spacecraft in the flyby orbit at time
            t:
```

```
    meanAnomalyFlyBy=2*pi*(t-periodMoon/2)/periodFlyby; % mean anomaly [rad]
    at t
    % find root
    ffb= @(E) E - eccentricityFlyby * sin(E) - meanAnomalyFlyBy;
    solFB=fzero(ffb, 0);

    % Now we calculate the true anomaly of the spacecraft from the eccentric
    anomaly:
    anglefb= pi + 2 * atan(sqrt((1 + eccentricityFlyby) / (1 -
    eccentricityFlyby)) * tan(solFB/2)); % the true anomaly [rad] from solFB

    % Location of spacecraft
    locationOfCraft= [(r_fb(anglefb)*cos(anglefb) +
    r_M(trueAnomalyMoon)*cos(trueAnomalyMoon)) (r_fb(anglefb)*sin(anglefb) +
    r_M(trueAnomalyMoon)*sin(trueAnomalyMoon))];
    [alpha, rho]= cart2pol(locationOfCraft(1), locationOfCraft(2));

    % Save location in table
    locationTableSpacecraft(i,1)= t/3600;
    locationTableSpacecraft(i,2)= alpha;
    locationTableSpacecraft(i,3)= rho;

    % Preparation for return orbit:
    orbitTilt= trueAnomalyMoon; % Tilt of the eventual return orbit
    apogeeReturn= r_M(trueAnomalyMoon); % Apogee of the eventual return orbit

    % Return orbital parameters
    eccentricityReturn= (apogeeReturn + semimajorAxisFlyby -
    9378)/(apogeeReturn + semimajorAxisFlyby + 9378); % eccentricity
    semimajorAxisReturn= (apogeeReturn + semimajorAxisFlyby + 9378)/2; %
    semimajor axis [km]
    periodReturn= 2 * pi * sqrt(semimajorAxisReturn^3 / gravParamEarth); %
    full period of motion [s]

else
    if t >= returnTime % return orbit

        % Spacecraft's radius [km] as function of true anomaly [rad] during
        return:
        r_r= @(phi) (semimajorAxisReturn * (1 - eccentricityReturn^2))./(1 +
        eccentricityReturn * cos(phi));

        % Now we find the location of the spacecraft in the return orbit at
        time t:
        meanAnomalyReturn= 2 * pi * (t - 1312200)/periodReturn + pi;
        % find root
        fr= @(eccentricAnomalyReturn) eccentricAnomalyReturn -
        eccentricityReturn * sin(eccentricAnomalyReturn) -
        meanAnomalyReturn;
        solR= fzero(fr, 0);

        % Now we calculate the ture anomaly of the spacecraft from the
        eccentric anomaly:
        trueAnomalyReturn= 2 * atan(sqrt((1 + eccentricityReturn) / (1 -
        eccentricityReturn)) * tan(solR/2));
```

```
                % Save location in table
                locationTableSpacecraft(i,1)= t/3600;
                locationTableSpacecraft(i,2)= trueAnomalyReturn + orbitTilt;
                locationTableSpacecraft(i,3)= -r_r(trueAnomalyReturn);

                % Complete the simulation once the spacecraft has completed return
                if t > returnTime + 0.5*periodReturn
                    break
                end

            end
        end
    end
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% PLOTTING FROM LOCATION TABLES

% Moon and Spacecraft location (iterative)
f1= figure('Color','w'); % create figure
pax= polaraxes;

% plot the Moon's orbit:
polarplot(theta, r_M(theta), 'Color', 'k', 'Linestyle', ':', "LineWidth", 2); hold
on;
% plot the Earth
polarplot(0,0,'-o','Color','g','MarkerSize',10,'MarkerFaceColor',[0.05 0.87 0.38])
rlim([0,5*10^5]);

% Open video recorder
vidfile= VideoWriter('Hohmann-Transfer.mp4','MPEG-4');
open(vidfile);

for i= 1:length(locationTableMoon)

    % plot Moon and spacecraft using location tables
    plotMoon= polarplot(locationTableMoon(i,2), locationTableMoon(i,3),'-
    o','Color','b','MarkerSize',10,'MarkerFaceColor','#D9FFFF');
    plotCraft= polarplot(locationTableSpacecraft(i,2),
    locationTableSpacecraft(i,3),'-o','Color','r','MarkerSize',5);

    % add respective time annotation
    str="t={"+round(locationTableMoon(i,1),0)+"} min"; % annotation text
    an=annotation('textbox','String',str,'FitBoxToText','on','Position', ...
        [0.541071428571428 0.426190477396766 0.14821428182934 0.0642857130794299]); %
    annotation formatting

    % write the current frame to the video file
    currframe=getframe(gcf);
    writeVideo(vidfile,currframe);

    delete(an); % refresh the annotation text
    delete(plotMoon); % refresh the moon plot
```

```
    if plotCraft ~= 0
        delete(plotCraft); % refresh the spacecraft plot (if necessary)
    end
end

close(vidfile); % close video file
```

13 Appendix B: Variables

h	Angular momentum [kg·km^2·s^{-1}]
r_a	Apogee radius of an orbit [km]
Δv	Difference in velocity (impulse) [km·s^{-1}]
E	Eccentric anomaly [rad]
e	Eccentricity of an orbit
v_f	Final velocity [km·s^{-1}]
M	Governing mass [kg]
v_i	Initial velocity [km·s^{-1}]
M_e	Mass of Earth [5.97·10^{24} kg]
M_a	Mean anomaly [rad]
r_p	Perigee radius of an orbit [km]
r	Radius of an object in orbit from its gravitational focus [km]
a	Semimajor axis of an ellipse [km]
μ	Standard gravitational constant of a governing body [km^3·s^{-2}]
T	Period of an orbit [s]
t	Time [s]
θ	True anomaly [rad]
G	Universal gravitational constant [6.67·10^{-20} N·km^2·kg^{-2}]

14 Authorship

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9 Conclusion	Will Perri and Benjamin Guilbault
10 Acknowledgements	Benjamin Guilbault, Camille Williams, Will Perri
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12 Appendix A: MATLAB	Camille Williams
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